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ROTORCRAFT CONVERTIBLE ENGINE STUDY

FINAL REPORT

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16. Abstract

Convertible propulsion systems for advanced rotorcraft are evaluated in terms of their impact on aircraft operating economics and fuel consumption. A variety of propulsion system concepts, including separate thrust and power producing engines, convertible fan/shaft engines, and auxiliary propeller configurations are presented. The merits of each are evaluated in two different rotorcraft missions: an inter-city, commercial transport of the ABC™ type, and an off-shore oil ring supply ship of the X-wing type. The variable inlet guide vane (VIGV) fan/shaft converting engine and auxiliary propeller configurations are shown to offer significant advantages over all the other systems evaluated, in terms of both direct operating cost (DOC) and fuel consumption.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES - Continued

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF TABLES - Continued

SUMMARY

SUMMARY

Two advanced rotorcraft were selected for this study to serve as the bases for evaluating a variety of propulsion system concepts; one of the ABC ™ (Advancing Blade Concept) type, and one of the X-Wing (stopped, circulation controlled rotor) type. The rotorcraft selected were a 48 passenger commercial airliner of 370 km (200 nmi) range, 463 km/h (250 kt) cruise speed for the ABC and a 48 passenger oil ring supply ship of 833 km (450 nmi) range and a higher cruise speed of 741 km/h (400 kt) for the X-Wing. These were chosen with the help of Boeing Vertol on the basis of market potential in the 1990's. Boeing Vertol also provided mission analysis support throughout the study.

Baseline, separate powerplants (i.e., two turboshafts to power the rotor and two turbofans to provide thrust) were defined in Task I. In Task II, baseline convertible engines of the variable inlet guide vane (VIGV) type were defined, and the advantages of powering the rotorcraft with two convertible engines rather than four separate engines demonstrated. The cycles of the baseline powerplants of Tasks I and II were selected based on prior General Electric experience. For example, the fan pressure ratios (1.36 for the ABC and 1.65 for the X-Wing) were selected based on prior turbofan aircraft mission studies as being appropriate to the flight speeds chosen for the two rotorcraft. Important characteristics of these baseline cycles are shown in Table 1.

TABLE 1. BASELINE CYCLE CHARACTERISTICS

	Task I Separate Engines		Task II Convertible
	Turboshaft	Turbofan	VIGV Turbofan
ABC ROTORCRAFT			
Fan Pressure Ratio	-	1.36	1.36
Bypass Ratio	-	8.5	3.9
Overall Cycle Pressure Ratio	21.6	31.3	22.3
Max T41, °C (°F)	1288 (2350)	1288 (2350)	1288 (2350)
X-WING ROTORCRAFT			
Fan Pressure Ratio	-	1.65	1.65
Bypass Ratio	-	6.1	2.7
Overall Cycle Pressure Ratio	21.6	32.1	24.1
Max T41, °C (°F)	1288 (2350)	1288 (2350)	1288 (2350)

The convertible engines were more efficient, weighed less, cost less and had lower projected maintenance costs. All these factors resulted in rotorcraft with lower gross weight, acquisition cost, block fuel, and Direct Operating Cost (DOC).

It was expected that two convertible turbofans would be superior to four separate engines. However, the choices of convertible powerplant cycle and type were further refined.

The following alternative powerplants were studied in Task III. (See figures in the Alternative Convertible Powerplant Configurations and Technologies section.)

TABLE 2. ALTERNATIVE POWERPLANTS SCREENED	
(Against VIGV Turbofan Base)	
ABC	X-Wing
VP Fan Remote Fan/Parallel LPT's Prop/Shaft* Prop/Shaft Variants: Remote Parallel LPT's (Close to GG's) Remote Parallel LPT's (Close to Prop) Remote Series LPT's Remote Parallel LPT's (Common to both GG's)	Remote Fan Prop/Shaft*
*Selected for mission analysis	

SUMMARY - Continued

The term "prop/shaft" was coined to describe the propulsion system concept wherein two turbo-shaft engines drive into the rotorcraft main gearbox, which distributes the power to the overhead rotor(s) and/or thrust producing propeller(s). The prop/shaft was considered a prime alternate for the ABC vehicle from the outset of the study. Four of the alternative systems were variations on the prop/shaft theme, with unusual turbomachinery arrangements, and were studied only on the ABC vehicle. Had any of them shown merit, they would have been extended to the X-Wing. Similarly, it was expected that the VP fan would show its merits, if any, at the lower fan pressure ratios suitable for the flight speed of the ABC. Had it shown a significant advantage, it too could have been investigated in the X-Wing framework.

None of these systems, in either aircraft, showed merit on the basis of powerplant weight and fuel except for the prop/shaft engines. As a result only the prop/shaft engines were carried through the same complete mission analysis as the separate and the VIGV convertible engines.

The results of cycle studies in Task IV validated the choice of cycle pressure ratio and fan Pressure Ratio for the VIGV turbofans, but indicated potential improvement for higher T41. It was also evident from the mission results of Task II that because cruise power settings were low, the design core pressure ratio and fan airflow were under-utilized. Accordingly, both the VIGV turbofans and the prop/shaft engines were refined in a consistent manner, utilizing a 1371°C (2500°F) T41 at the OEI takeoff point.

The features of the refined convertible powerplants are summarized in Table 3. These refined convertible powerplants, when evaluated in the Boeing Vertol rotorcraft, yielded the results shown in Table 4 for the ABC and X-Wing.

The prop/shaft engine was identified as the "preferred" powerplant in the case of the ABC rotorcraft because of its clear advantages in gross weight, acquisition cost, block fuel and DOC.

The VIGV turbofan was selected as the "preferred" powerplant for the X-Wing rotorcraft even though there is a DOC advantage for the prop/shaft for nominal fuel costs and utilization. This DOC result is consistent with studies of advanced turboprops and turbofans for conventional transport aircraft. Considering that the DOC advantage would reduce to zero for \$.264/1 (\$1/gal) fuel and 360 hr/year utilization (typical of a military application) and that a turbofan becomes more suitable as flight speed is increased above 741 km/h (400 kt), the VIGV turbofan was chosen as the preferred powerplant. The prop/shaft engine undoubtedly also has merits for the X-Wing and should receive continued attention.

TABLE 3. FEATURES OF REFINED CONVERTIBLE POWERPLANTS				
	ABC		X-Wing	
	VIGV Turbofan	Prop/Shaft	VIGV Turbofan	Prop/Shaft
<u>OEI Hover, SLS, ISA +15°C (27°F)</u>				
Output Power, kW	3655	3587	7416	7653
(hp)	(4900)	(4810)	(9945)	(10260)
T41, °C	1371	1371	1371	1371
(°F)	(2500)	(2500)	(2500)	(2500)
Overall Cycle Pressure Ratio	27.5	21.6	30.6	22
<u>Design Cruise, ISA +10°C (18°F)</u>				
Altitude, m	3048	3048	9144	9144
(ft)	(10000)	(10000)	(30000)	(30000)
True Airspeed, km/h	463	463	741	741
(kt)	(250)	(250)	(400)	(400)
Thrust, N	7515	222	10585	-67
(lbf)	(1690)	(50)	(2380)	(-15)
Output Power, kW	1255	2461	231	2808
(hp)	(1685)	(3300)	(310)	(3765)
Inlet Corrected Flow kg/s	74.4	12.4	139	21.0
(lbm/sec)	(164)	(27.2)	(307)	(46.3)
Fan Pressure Ratio	1.36	-	1.65	-
Overall Cycle Pressure Ratio	24.1	19.7	28.9	19.6
T41, °C	1204	1207	1124	1079
(°F)	(2200)	(2205)	(2055)	(1975)
Weight, kg	549	403	968	594
(lbm)	(1210)	(890)	(2135)	(1310)
Overall Length, m	2.59	1.79	3.84	1.23
(in)	(102)	(70)	(151)	(72)
Inlet Diameter, m	0.97	0.68	1.32	0.59
(in)	(38)	(27)	(52)	(23)

<u>SUMMARY</u> - Continued

The comparison to the separately powered rotorcraft was also updated with refined separate and convertible powerplants, with the results shown in Table 5.

The overall result of the study was that convertible engines show significant payoff vs. separate shaft and thrust producing powerplants. For the ABC rotorcraft, a prop/shaft engine was the best entry among the systems studied. For the X-Wing rotorcraft, the convertible VIGV turbofan and the prop/shaft engine both have merits to be considered.

Advanced technology features associated with the selected convertible engine and prop/shaft systems which merit R&D effort are: VIGV fan technology emphasizing closed IGV operation, integrated engine/rotorcraft control, bleed compressor systems for X-Wing rotorcraft, exhaust torque reaction systems for the X-Wing, and shafts and bearings in the power train from engine to rotor and/or propeller.

TABLE 4. EVALUATION OF REFINED CONVERTIBLE POWERPLANTS			
	ABC		
	Refined VIGV Turbofan	Refined Prop/Shaft "Preferred"	% Difference
Gross Weight, kg (lbm)	15610 (34410)	15300 (33730)	-2.0
A/C Acquisition Cost, $\$X10^{-6}$	7.15	6.69	-6.4
Block Fuel, kg (lbm)	940 (2070)	800 (1770)	-14.4
DOC, ¢/seat·km (¢/seat·nmi) at Fuel Cost \$.528/l (\$2.00/gal)	8.5 (15.7)	7.6 (14.0)	-10.8
DOC, ¢/seat·km (¢/seat·nmi) at Fuel Cost \$.264/l (\$1.00/gal)	6.8 (12.5)	6.1 (11.3)	-9.6
	X-WING		
	Refined VIGV Turbofan "Preferred"	Refined Prop/Shaft	% Difference
Gross Weight, kg (lbm)	19935 (43950)	20370 (44900)	+2.2
A/C Acquisition Cost, $\$X10^{-6}$	9.89	9.83	-0.6
Block Fuel, kg (lbm)	1750 (3860)	1450 (3195)	-17.2
DOC, ¢/seat·km (¢/seat·nmi) at Fuel Cost \$.594/l (\$2.25/gal)	7.5 (13.9)	7.1 (13.1)	-5.8
DOC, ¢/seat·km (¢/seat·nmi) at Fuel Cost \$.330/l (\$1.25/gal)	6.1 (11.3)	5.9 (10.9)	-3.5

TABLE 5. FINAL BENEFIT ASSESSMENT			
	Separate Engines	VIGV Turbofan Engines	Prop/Shaft Engines
	ABC		
% Change In:			
Gross Weight	Base	-7.2	-9.1
Acquisition Cost	Base	-12.1	-17.7
Block Fuel	Base	-15.1	-27.3
DOC @ \$.528/l (\$2.00/gal)	Base	-12.7	-22.1
DOC @ \$.264/l (\$1.00 gal)	Base	-12.1	-20.8
	X-WING		
Gross Weight	Base	-15.3	-13.4
Acquisition Cost	Base	-18.1	-18.6
Block Fuel	Base	-16.1	-30.0
DOC @ \$.594/l (\$2.25/gal)	Base	-20.8	-25.3
DOC @ \$.330/l (\$1.25/gal)	Base	-21.8	-24.2

INTRODUCTION

TASK I

DEFINITION OF BASELINE AIRCRAFT AND MISSION

INTRODUCTION

This study of propulsion systems for advanced high speed rotorcraft was sponsored by NASA Lewis Research Center with two purposes in mind: The first was to evaluate a variety of propulsion systems suitable for advanced rotorcraft. The second purpose was to identify technologies and R&D programs required to prepare for the future use of the selected propulsion systems.

In order to evaluate a variety of rotorcraft concepts, NASA assigned different systems to each of the engine contractors, matching them suitably with the rotorcraft subcontractors. General Electric Co. was assigned the X-Wing and Advancing Blade Concept (ABC) TM rotorcraft, with Boeing-Vertol as the rotorcraft subcontractor to General Electric Co.

The study was organized into six tasks which built successively on information and results as they were developed. During Task I, suitable commercial missions for the two rotorcraft types were identified and baseline designs using separate turbofan and turboshaft powerplants were established. The ABC mission and market was identified as a 48 passenger, intercity, scheduled transport cruising at 463 km/h (250 knots). The X-Wing mission and market was chosen as a 48 passenger, 741 km/h (400 knot), oil rig supply transport vehicle.

During Task II the separate powerplants were replaced in the two rotorcraft by convertible variable inlet guide vane (VIGV) turbofans and a mission merit factor comparison completed, on the basis of evaluation criteria established in Task I. The primary quantitative merit factor in this study was DOC, with consideration also being given to fuel burned and acquisition cost on a quantitative basis, and community acceptance, passenger acceptance, reliability, operability, and program risk as qualitative secondary characteristics.

Alternate propulsion systems and cycles were considered in Tasks III and IV to permit the selection of the best, refined system for each rotorcraft.

One powerplant was selected during Task V for each of the two rotorcraft and a benefit analysis relative to the separate engine powered rotorcraft was conducted in Task VI. At the conclusion of the study, as part of Task VII, technologies required and R&D programs were recommended to NASA.

This study was not intended as a comparison between rotorcraft types. Its purpose was to evaluate the propulsion alternatives for an ABC and an X-Wing rotorcraft in a systematic and equitable manner.

TASK I - DEFINITION OF BASELINE AIRCRAFT AND MISSION

MISSION GROUND RULES

Aircraft Definition

Prior studies of civil rotorcraft have indicated a potential for large improvements in safety, productivity, and economics for several advanced aircraft concepts (refs. 1 and 2). Two of these concepts, the ABC and X-wing configurations, have shown promise using convertible engine arrangements and have (or will have) the benefit of near full-scale flight demonstration programs. Further government-funded development could lead to commercialization of these concepts in the early 1990's.

Design Mission Definition

Since the two selected concepts differ greatly, different study missions were selected for each based on their fundamental characteristics and probable flight speed regimes. The ABC is generally considered appropriate at speeds of 463-556 km/h (250-300 kt), and its lift and drag characteristics tend to limit the concept to moderate altitudes and relatively low range. The X-Wing has a relatively higher subsonic speed capability of 741-926 km/h (400-500 kt), along with high altitude and long range potential. These two sets of characteristics, examined against anticipated future civil missions, appear to satisfy the basic requirements for a short-haul commercial transport mission, and an offshore oil crew transport mission, respectively.

Table 6 presents the mission analysis ground rules adopted for the two rotorcraft. Figures 1 and 2 provide the mission profiles used in performing the economic analysis necessary to arrive at the Direct Operation Cost (DOC), and Figures 3 and 4 show the simplified profiles used in the aircraft sizing program to establish aircraft design characteristics and weights.

Short Haul Commercial Transport Mission (ABC Concept): Conventional, fixed wing airplanes provide increasingly economical, fuel-efficient services from airport-to-airport as range increases. However, as stage lengths between population centers decrease, the typical fixed wing airplane, contrary to a VSTOL aircraft, suffers from much-reduced fuel efficiencies due to the time spent in terminal maneuvers, traffic delays, and alternate weather routing, (Fig. 5 and ref. 3). When block time (airport-to-airport) is added to the terminal and ground transportation time requirements, the need for a time-saving vertical lift, short-haul transportation system eliminating (or reducing) the airport congestion constraints is indicated. (Fig. 6 and ref. 2).

Figure 7 (ref. 4) indicates that the median stage length for short-haul operations is 306 km (190 statute mi). Typical high-density city-pairs with stage lengths in this category offering potential for advanced rotorcraft services, are New York-Washington, Chicago-Detroit, and London-Paris.

Many of these potential routes are in the vicinity of 370 km (200 nmi) which, combined with probable winds and reserve fuel allowances, results in a still-air design range requirement of about 556 km (300 nmi).

While operating economics generally favor larger aircraft, it is not likely that potential ABC rotorcraft for the early 1990's would exceed the capability of carrying 48 passengers since this size has been shown to be compatible with a potential mid-80's military program (ref. 2).

Civil operators have flown, and for the near future will continue to fly, their routes under Category A VTOL rules for one-engine inoperative (OEI) situations. However, when projecting an advanced aircraft more than 10 years in the future, it is logical and reasonable to require hover-out-of-ground-effect under OEI conditions, albeit using a 2-1/2 minute contingency rating on the remaining engines. The safety, flexibility, and operational benefits accuracy from this requirement would seem to justify the cost penalty of adding this requirement to a new aircraft/engine program.

TABLE 6. MISSION GROUNDRULES		
	ABC	X-WING
APPLICATION	Commercial Airliner	Oil Rig Transport
DESIGN MISSION FOR AIRCRAFT SIZING		
Payload, No. of Passengers	48	48
Still Air Range, km (nmi)	370 (200)	833 (450)
Still Air Reserves km (nmi)	185 (100)	278 (150)
Cruise Speed, km/h (kt)	463 (250)	741 (400)
Cruise Altitude, m (kt)	3048 (10000)	9144 (30000)
Ambient Conditions		
Takeoff, °C (°F)	ISA + 15 (27)	ISA + 15 (27)
Cruise, °C (°F)	ISA + 10 (18)	ISA + 10 (18)
OEI Criteria		
Takeoff	Hover OGE at Takeoff Rating	
Enroute	Category A, 150 ft/min ROC	
Altitude, m (ft)	610 (2000)	305 (1000)
OFF-DESIGN MISSION FOR ECONOMIC ANALYSIS		
Load Factor, %	65	85
Payload, No Passengers	31	41
Still Air Range, km (nmi)	370 (200)	833 (450)
Still Air Reserves, km (nmi)	185 (100)	278 (150)
Cruise Speed, km/h (kt)	463 (250)	741 (400)
Cruise Altitude, m (ft)	3048 (10000)	9144 (30000)
Ambient Conditions	ISA	ISA

TASK I - DEFINITION OF BASELINE AIRCRAFT AND MISSION - Continued

MISSION GROUND RULES - Continued

Offshore Oil Crew Transport Mission (X-Wing Concept): During the past decade, offshore oil operations have generally been limited to 370 km (200 miles) or less offshore (due to rig construction constraints). However, in the period beyond 1985, the petroleum industry is expected to extend operations up to possibly 926 km (500 nm) offshore using advanced deep-water rigs. Therefore, higher speed capability for the crew-change and supply transport operations should pay off through use of a more efficient aircraft as well as the much-reduced "portal-to-portal" time.

Selecting a mission range of 833 km (450 nmi), combined with headwind and alternate routing allowances of 278 km (150 nmi), a still-air design range of 1111 km (600 nmi) is recommended.

In this mission, an OGE hover capability with one engine inoperative is also desirable due to the rig platform size constraints; it is the only way to provide for a safe landing at the rig under OEI conditions.

Based on the British Airways Civil 234 Chinook operations, a 48-passenger capacity is appropriate for the oil rig mission. Many oil rigs have been (or will be) converted to handle an aircraft of this size class. Future deep-water rigs will have adequate platforms for this also.

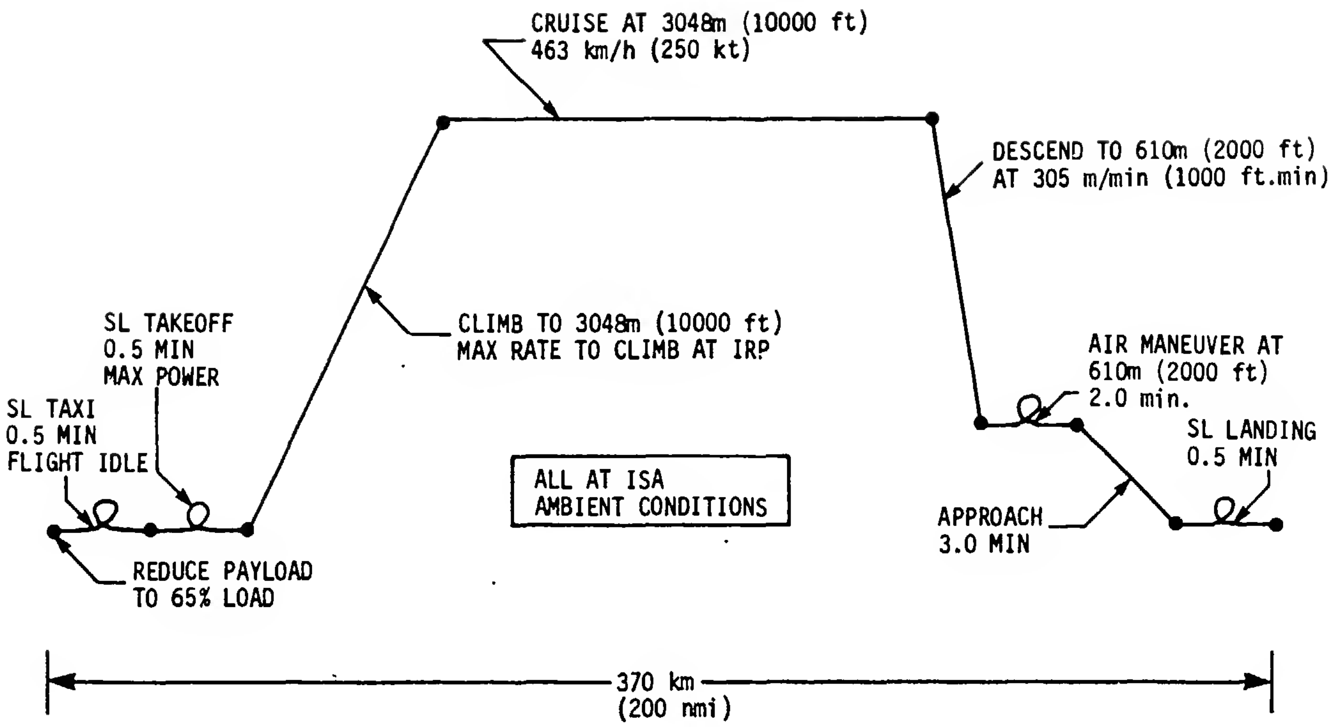

Figure 1. ARP Economic Mission Profile.

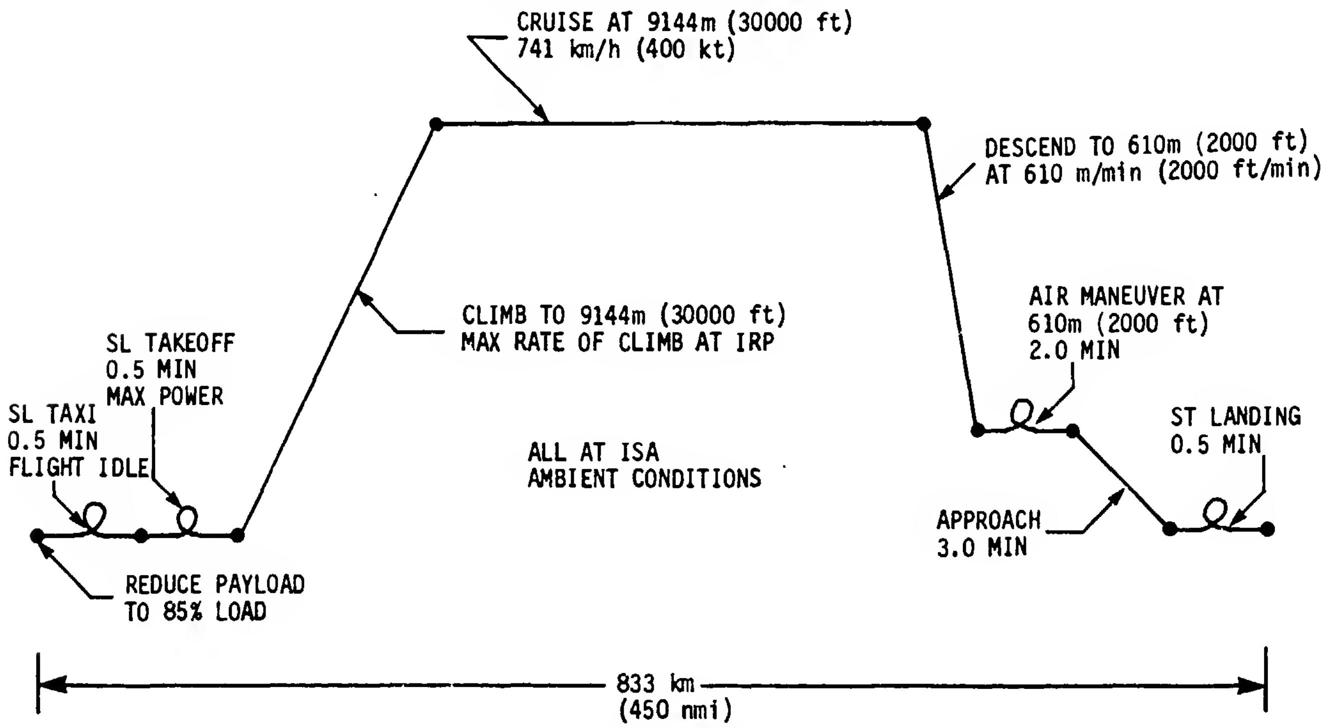

Figure 2. X-Wing Economic Mission Profile.

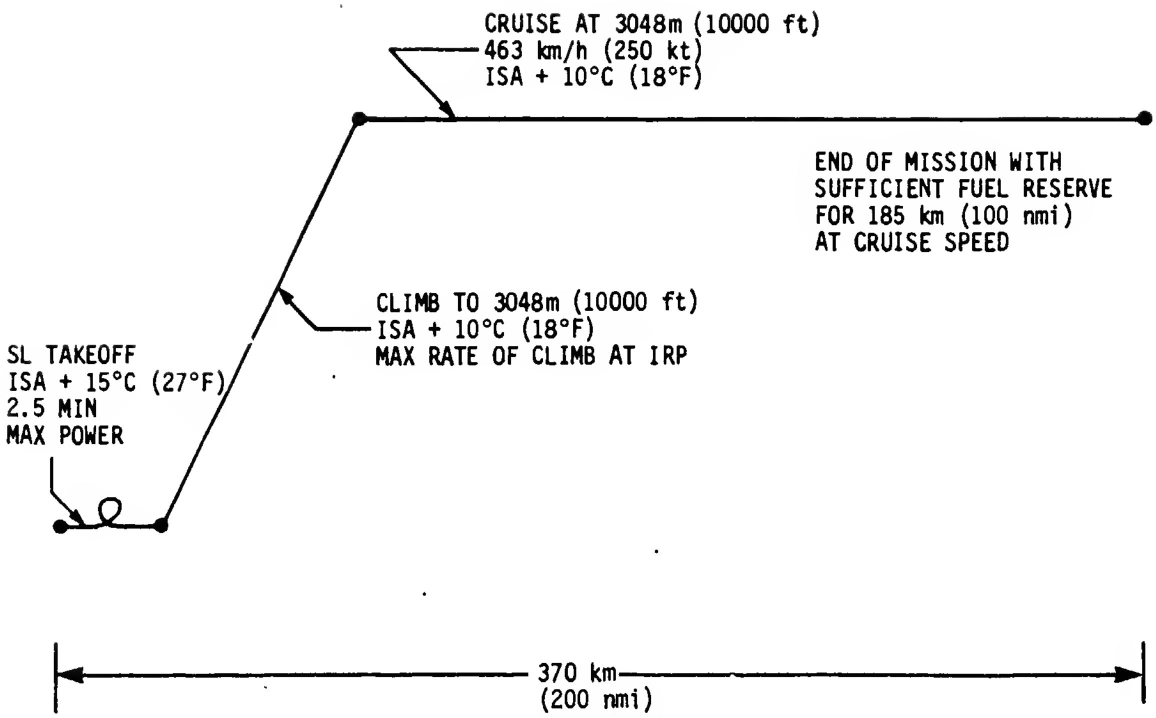

Figure 3. ABC Design Mission Profile

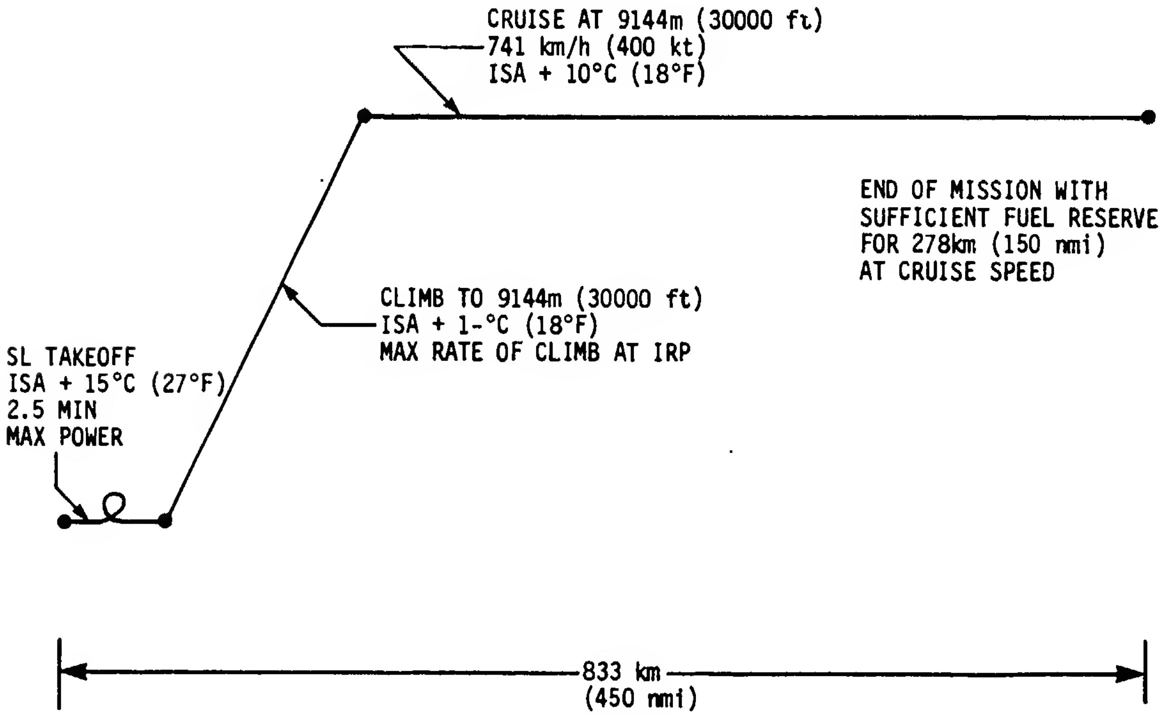

Figure 4. X-Wing Design Mission Profile

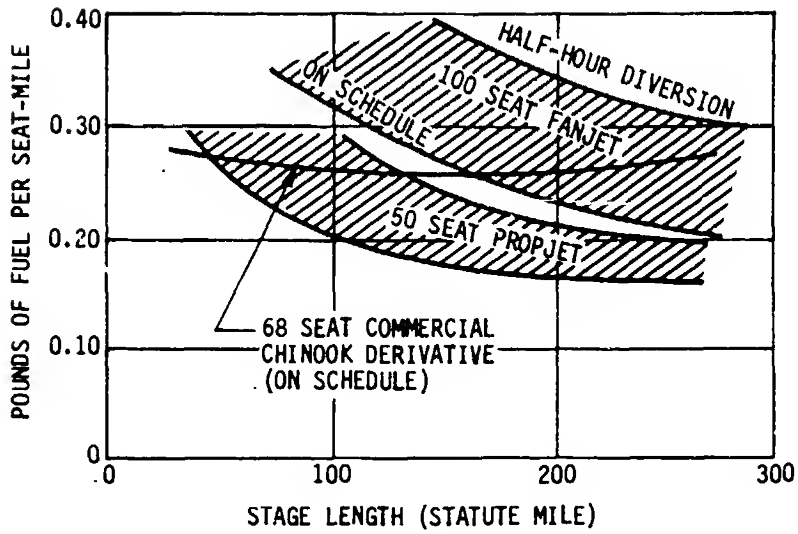

Figure 5. Fuel Usage Comparison - Fixed Wing and Rotorcraft

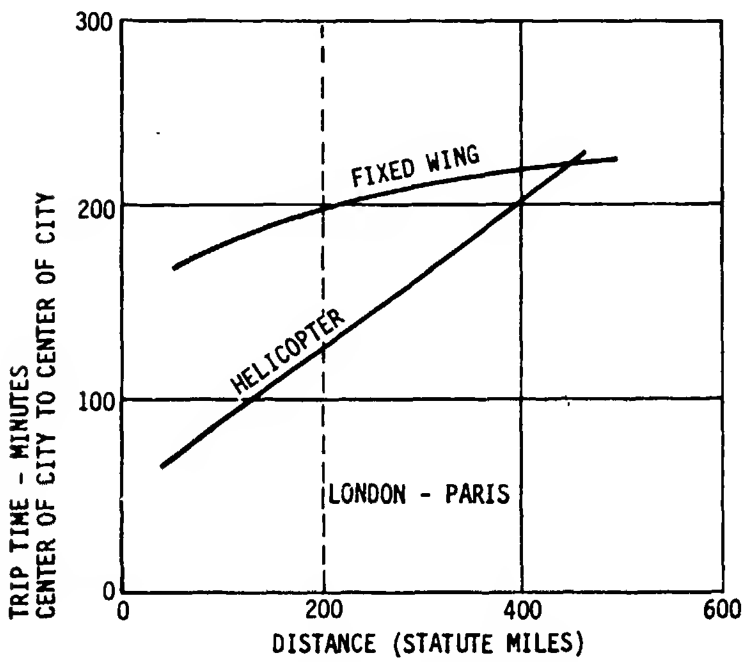

Figure 6. City Center Trip Times

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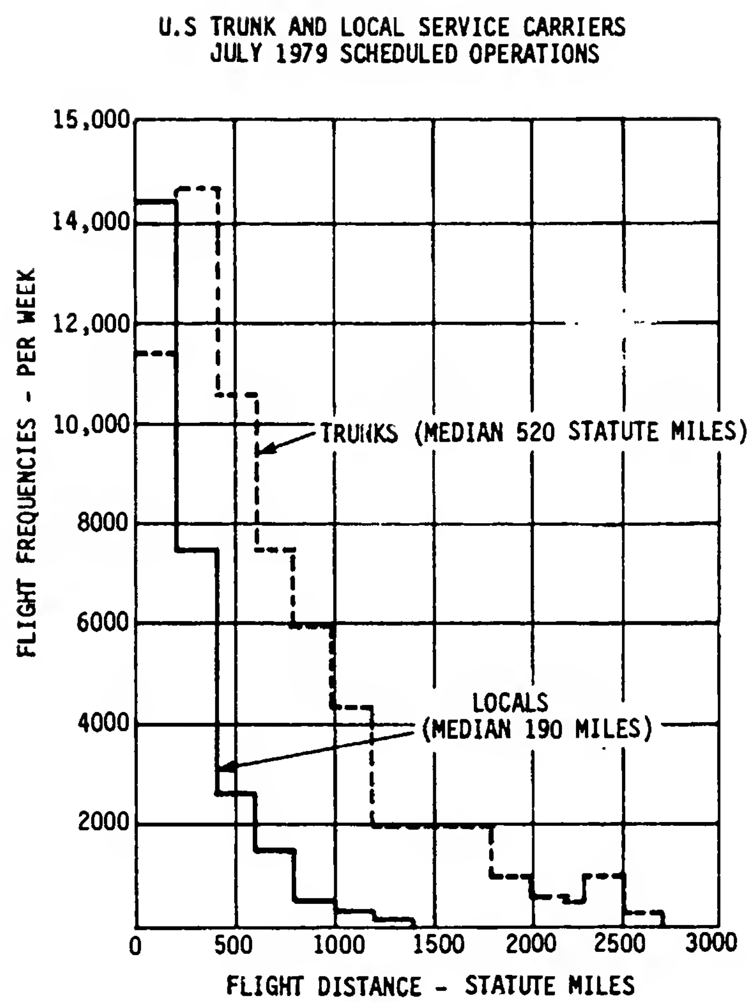


Figure 7. Flight Frequencies vs Stage Length

MISSION GROUNDRULES - Continued

Off-Design Mission Definition: Since design mission profiles are rarely flown during the lifetime of an aircraft, an off-design mission is more representative for cost evaluations. The usual variant is passenger load factor; typical load factors for short-haul airline-type missions are around 65% and that value is used for the ABC commercial airlines mission.

However, the oil rig transport mission has, to date, been a contract operation; since the oil company is paying a flat fee, the company will schedule crew turnarounds such that high passenger load factors can be achieved. Based on previous North Sea Oil operations, a load factor of 85% was selected. The off-design missions are flown under ISA conditions, because this is most representative of the average conditions encountered in service.

AIRCRAFT DESIGN AND SIZING PROCEDURE

Aircraft sizing and performance studies were conducted for 3 propulsion system variants of the ABC and X-Wing vehicle concepts. The propulsion system variants consist of: (1) separate turboshaft and turbofan engines, (2) convertible engines, and (3) turboshaft engines with auxiliary propellers. General groundrules were established to maintain a consistent approach to sizing the various aircraft. All aerodynamic and structural technology levels and economic methodology were held constant throughout the study. A disc loading of 73.2 kg/m^2 (15 lb/ft^2), which permits safe ground operations, was selected for all aircraft. Engine and propeller performance, weights, and costs were provided to Boeing Vertol by General Electric. All aircraft sizing and performance data were obtained from the Boeing Vertol developed computer programs HESCOMP and VASCOMP (ref. 5 and 6). The use of these computerized aircraft sizing programs allows the configuration analyst to rapidly and systematically assess the effects of design variables and determine their impact on overall vehicle size and performance.

The V/STOL Aircraft Sizing and Performance Computer Program (VASCOMP) was used for sizing the X-Wing concepts. The Helicopter Sizing and Performance Computer Program (HESCOMP), was used for the ABC co-axial helicopter configurations.

The programs consist of geometry (design), weight, aerodynamic, propulsion, and performance modules. The modules contain size trend equations which reflect the variation of aircraft dimensions with gross weight, detailed statistical weight trend equations, routines for sizing engines, propellers and rotors to match airframe requirements, and a library of engine and rotor data. Inputs to the programs consist of a series of single point values and tables specifying, for example, fuselage geometry, type of propulsion system, mission profile and fixed weights.

The programs calculate aircraft sizing, weight, propulsion and aerodynamic information and mission performance data. The performance data is a time history of the mission, including speed, distance, power and/or thrust levels, fuel used, etc.

ECONOMIC EVALUATION PROCEDURE

In order to evaluate the suitability of convertible engine concepts for the ABC and X-Wing type rotorcraft, a cost estimating method was required that is sensitive to the variable engineering parameters of these aircraft systems. The computer programs, (HESCOMP and VASCOMP) provide sufficient component system weight breakdown and mission data details to use the methodology of NASA CR152315, "Parametric Study of Helicopter Aircraft System Costs and Weights" and a modified AIA method of estimating direct operating costs (ref. 7).

Acquisition Cost Estimate

Using the output of the HESCOMP and VASCOMP computer programs, the NASA parametric acquisition cost estimating approach was used to estimate acquisition costs. The Cost Estimating Relationships (CERs) are shown in Table 7 as an indication of the level of detail employed in the analysis. Since the method provides costs in 1977 dollars, a factor of 1.50 was used to adjust the costs to the study year (1981) dollars.

Acquisition costs were determined based on the following ground rules:

1. Constant January 1981 dollars.
2. 500 aircraft of each type produced.
3. Development/certification costs spread over first 100 units.

Direct Operating Cost (DOC)

A specially modified AIA method (ref. 7) was used in this study to calculate DOC. The advantages of this method are that the VTOL flight profile is recognized, and that the effects of inflation are calculated for personnel expenses, aircraft price, and fuel price, before entering the formulae. Modifications to the formulae adopted for this study are in the areas of flight crew expenses and maintenance burden, where Boeing procedures reflecting more recent air carrier history were applied.

Direct operating costs were determined based on the following ground rules:

1. Annual utilization: 2,500 hours for short haul.
   2,000 hours for offshore oil.
2. Constant January 1981 dollars.
3. Fuel cost: \$2.00 per gallon for short haul.
   \$2.25 per gallon for offshore oil.
4. Depreciation: 10 years to 0%.
5. Insurance Rate: 1.5% of flyaway price/year.

The X-Wing fuel cost assumption is higher, to account for the additional transportation costs incurred in getting fuel out to the rig.

TABLE 7. SUMMARY OF HELICOPTER SYSTEM COST ESTIMATING RELATIONSHIPS
(Fiscal Year 1977 Dollars)

System	Equation*	Notes
1. Wing	$C_1 = 1015W_1^{0.968}Q^{-0.306}$	
2. Rotor	$C_2 = -12,936 + 100W_2Q^{-0.0740}$	
3. Tail		
A. Tail Rotor	$C_{3A} = 100W_{3A}Q^{-0.0740}$	
B. Tail Structure	$C_{3B} = 750W_{3B}^{0.968}Q^{-0.306}$	
4. Body	$C_4 = 560W_4^{0.968}Q^{-0.306}$	
5. Alighting Gear		
Total Wheeled	$C_5 = 94W_5Q^{-0.2176}$	
A. Structure	$C_{5A} = 200W_{5A}Q^{-0.306}$	
B. Controls	$C_{5B} = 120W_{5B}Q^{-0.0896}$	
C. Rolling Assembly	$C_{5C} = 26W_{5C}Q^{-0.0896}$	
or,		
Total Skid	$C_5 = \frac{W_5}{W_4} C_4$	
6. Nacelle	$C_6 = 660W_6^{0.968}Q^{-0.306}$	
7. Propulsion		
A. Powerplant	General Electric Supplied	
B. Drive	$C_{7B} = -4736 + 297W_{7B}Q^{-0.0740}$	W_{7B} <700 lbs
	$C_{7B} = 16,623 + 93W_{7B}Q^{-0.0740}$	W_{7B} >1,000 lbs
	$C_{7B} = 13,046 + 93W_{7B}Q^{-0.0740}$	All other 7B
C. Fuel	$C_{7C} = 26W_{7C}Q^{-0.0896}$	
D. Other	$C_{7D} = 140W_{7D}Q^{-0.0896}$	

* Subscripts refer to the numbers in the left hand column. For example, W_1 = Wing Weight.

System	Equation	Notes
8. Flight Controls	$C_8 = 150W_8Q^{-0.0896}$	
9. Auxiliary Power	$C_9 = 224W_9Q^{-0.0896}$	
10. Instruments		
Total Instruments	$C_{10} = 120W_{10}Q^{-0.0896}$	
A. Equipment	$C_{10A} = 110W_{10}$	
B. Installation, Misc.	$C_{10B} = 140W_{10B}Q^{-0.104}$	
11. Hydraulics	$C_{11} = 26W_{11}Q^{-0.0896}$	
12. Pneumatics	$C_{12} = 127W_{12}Q^{-0.0896}$	
13. Electrical	$C_{13} = 140W_{13}Q^{-0.0896}$	
14. Avionics		
Total Avionics	$C_{14} = 8047 + 120W_{14}Q^{-0.0896}$	
A. Equipment	$C_{14A} = 13,000 + 110W_{14A}$	
B. Installation, Misc.	$C_{14B} = 120W_{14B}Q^{-0.104}$	
15. Furnishings & Equipment	$C_{15} = 26W_{15}Q^{-0.0896}$	
16. Air Conditioning & Heat	$C_{16} = 300W_{16}Q^{-0.0896}$	
17. Anti-Icing	$C_{17} = 112W_{17}Q^{-0.0896}$	
18. Load and Handling	$C_{18} = \frac{W_{18}}{W_4} C_4$	
19. In-House Assembly	$C_{19} = 0.308\left[\sum_{i=1}^{18} C_i - \sum_j C_j\right] Q^{-0.0896}$	Single: j = (5C,7A,10,14)
	$C_{19} = 10.776\left[\sum_{i=1}^{18} C_i - \sum_j C_j\right] Q^{-0.3000}$	Tandem: j = (5C,7A,10,14)

Where: C = Cumulative average unit for Q units in constant 1977 dollars.
W = Weight of system or subsystem.
Q = Production quantity.

ABC VEHICLE CONCEPT

The objective of the Advancing Blade Concept is to extend the helicopter's operational envelope to the high speed flight regime. In simplest terms, the lift on a conventional helicopter rotor is limited by retreating blade stall, the requirement to maintain roll trim, and compressibility effects on the advancing blade. The requirement for roll trim precludes taking advantage of all the lift that can be produced by the high dynamic pressure acting on the advancing blades. In the ABC, rigid, counter-rotating, coaxial rotors are used to permit significant increases in advancing blade lift on each disc while maintaining lateral symmetry. Lateral cyclic pitch is employed on each disc to optimize the lateral displacement of the lift vector and obtain optimum rotor performance. The retreating side of each disc operates in an essentially unloaded condition. Figure 8 shows the comparison between conventional and ABC blade load distributions in forward flight. In the conventional rotor, the lift generated by the advancing blades must be reduced to balance the retreating blade-lift. The lift distribution of the ABC exhibits characteristics similar to those of a fixed wing aircraft in that lift is symmetrical about the aircraft longitudinal axis.

Figure 9 is a comparison of the maximum rotor lift coefficients of the ABC and a conventional articulated rotor as a function of advance ratio. For both rotors, these lift coefficients represent the maximum obtained in the NASA Ames 12 m x 24 m (40 ft x 80 ft) wind tunnel. In all cases the rotor systems were trimmed with regard to net pitching and rolling moments. These data tend to substantiate the forward flight load distributions given in Figure 8. For the conventional articulated rotor, lift decreases with advance ratio because of the reduced lifting capability of the retreating blades. The lift of the ABC tends to increase with advance ratio because the retreating blade of both rotor discs are unloaded and advancing blade lift is increased.

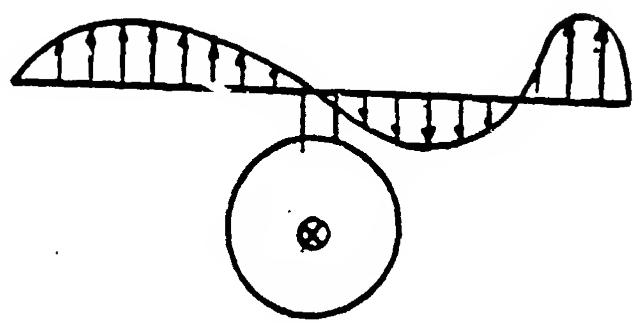
To avoid adverse compressibility effects on the advancing blades, the rotor is slowed at high forward speed. The ABC operates at a tip speed of 204 m/s (670 ft/sec) until the advancing tip Mach number is 0.9. Beyond this, the rotor is slowed to maintain this Mach number. This imposes an output shaft speed schedule on the engines, which can compromise engine performance.

The coaxial ABC is balanced in torque when both rotors require the same power. Because of this inherent feature, an antitorque tail rotor is not required for this configuration. Yaw control in hover and low speed is achieved by using differential collective pitch. Pitch is increased on one disc and decreased on the other. This produces a differential torque which is used for yaw control.

To carry large rolling moments without exceeding the maximum allowable tip deflections, as limited by the axial separation of the hubs, it is necessary that extremely stiff blades be used. The blades are much stiffer in flapping than those used on conventional helicopters. The stiffer blades a larger rolling moment and therefore require higher control power.

- CONVENTIONAL ROTOR

  ADVANCING BLADE LIFT REDUCED TO BALANCE RETREATING BLADE LIFT (MOMENTS TRIMMED)



- ABC ROTOR

  HIGH LIFT CARRIED ON ADVANCING BLADE OF EACH ROTOR. ROLLING MOMENTS TRIMMED BECAUSE OF CO-AXIAL CONFIGURATION

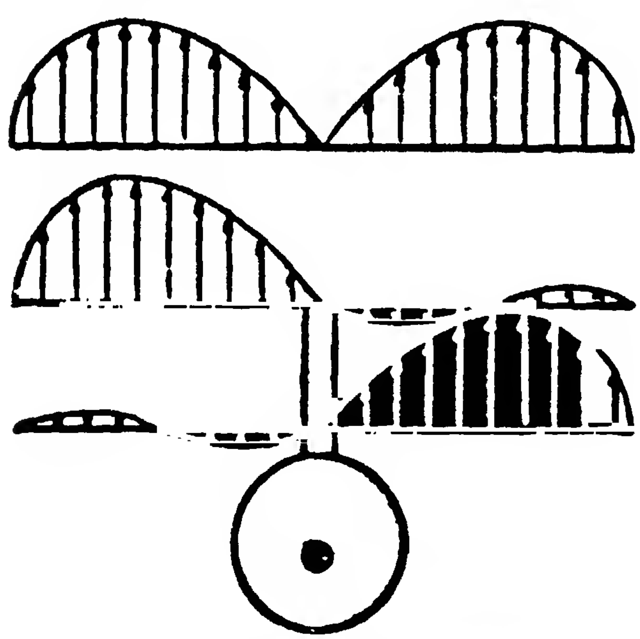


Figure 8. Comparison of Conventional and ABC Load Distributions in Forward Flight

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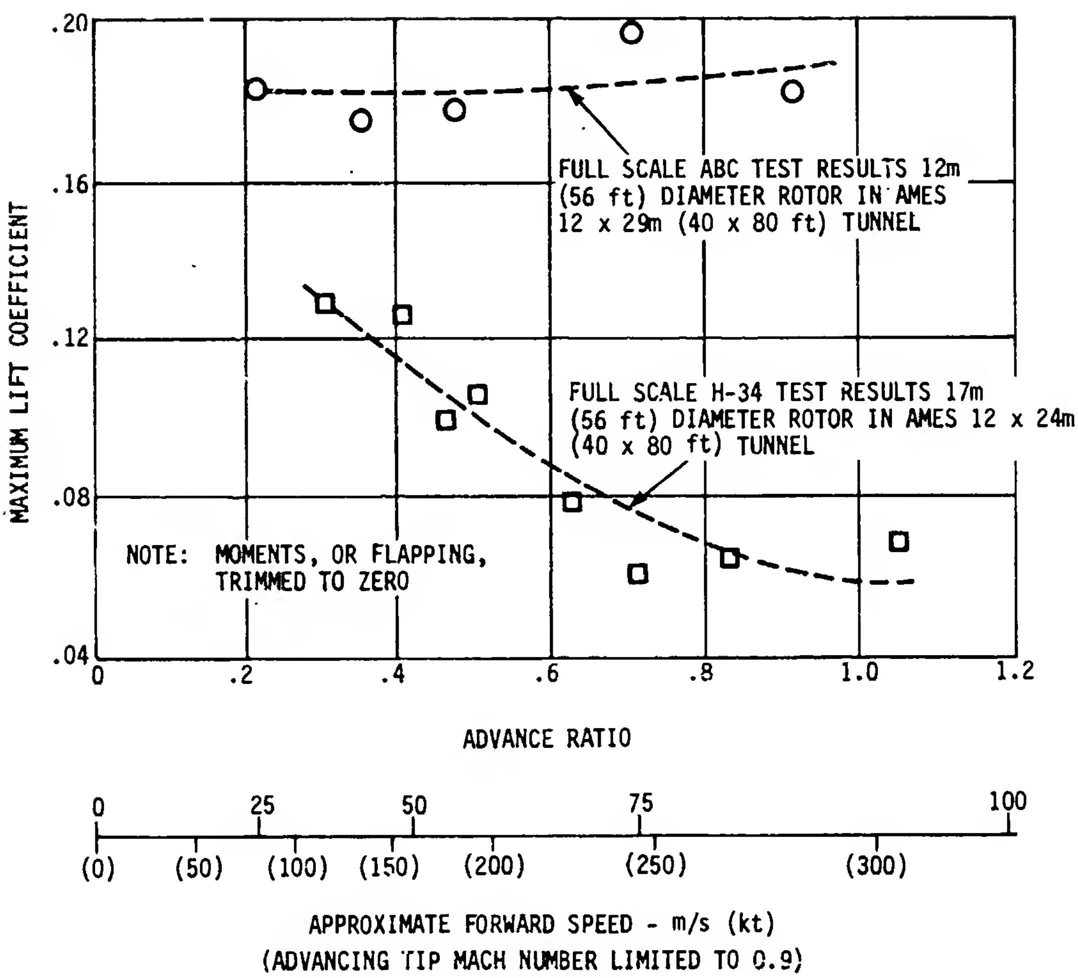

Figure 9. Comparison of Rotor Lift Achieved by ABC and by Typical Articulated Rotor as a Function of Advance Ratio - ABC Technical Concept

X-WING VEHICLE CONCEPT

The X-Wing is a stopped rotor V/STOL which uses circulation control aerodynamic technology. Features include four highly loaded rotor blades of moderate aspect ratio, which are stopped in-flight at the 45-degree azimuth position. Propellers or fans provide the thrust required for high speed forward flight. The high wing sweep, in conjunction with the high critical Mach number characteristics of circulation control airfoils permits, the wing to have high drag-divergence Mach number.

The circulation controlled rotor/wing employs a thin sheet of air ejected tangentially over the rounded trailing edge (Coanda blowing) of a quasi-elliptical airfoil. This increases lift proportional to the amount of blowing. Hover and low speed helicopter flight employ trailing edge blowing with aerodynamic cyclic and collective pitch modulation to provide trim and control. Above an advance ratio of approximately 0.6, simultaneous leading and trailing edge (dual) blowing is employed to maintain lift in the reverse flow region. Cyclic blowing is used to redistribute lift to the fore and aft regions of the rotor. The rotor is shaft driven and requires a compressor to provide blowing air. Conversion to fixed wing mode is accomplished at approximately 370-417 km/h (200 to 225 knots) with sea level standard atmosphere as the design condition. The rotor RPM is rapidly reduced to zero and locked. Blowing, coupled with a lifting tail and automatic rotor moment feedback systems provide the required trim and control throughout the flight envelope. Required conversion power is not expected to exceed the required hover power. Therefore, conversion was not considered during aircraft sizing since the engines were sized to an OEI condition. Since the compressor power requirements (at constant speed) are highest during the conversion cycle, it is probably not practical to slow the convertible engines (and compressors) down. However, until compressor requirements can be accurately determined for the full-scale aircraft, this should be an open question.

An anti-torque device is required during operation in the rotary wing mode. A parametric study of antitorque concepts including conventional tail rotors, Fenestron, and compressed air thrustor anti-torque systems was conducted. Table 8 illustrates the power required breakdown of the various anti-torque systems under consideration for the configurations examined. Since the X-Wing will primarily operate in the high speed fixed wing mode the Fenestron configuration was selected due to its low drag and moderate power required.

With the clutch/drive system visualized at this time, the clutch torque requirements are not excessive and approximate those of the demonstrated DDA V/STOL clutch (ref. 8). Compressors probably will need to be at constant speed during conversion. Therefore, there is no reduction in fan speed prior to reconversion. Due to differences in the rotor and fan drives (2.38:1 ratio vs. 75:1 ratio), the DDA clutch is approximately the right size (Table 9).

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TABLE 8. ANTI-TORQUE CONCEPT TRADE-OFF ANALYSIS - X-WING

(Separate Engines)

Gross Weight: 13608 kg (30,000 Lb)
Anti-Torque Thrust: 1202 kg (2560 Lb)
All Engines Operating Hover Analysis

	Tail Rotor	Fenestron	Thrustor (Compressor Air)
Size, m (ft)	4.48 (14.7)	1.98 (6.5)	.37 x .37 (1.2 x 1.2)
Equivalent Anti-Torque Power, kW (hp)	280 (375)	522 (700)	3430 (4600)
Compressor Power, kW (hp)	559 (750)	559 (750)	559 (750)
Rotor Power, kW (hp)	3057 (4100)	3057 (4100)	3057 (4100)
Total Power Required, kW (hp)	3896 (5225)	4139 (5550)	7047 (9450)
System Weight	Low	Mod	High
High-Speed Compatibility	Poor	Closures Required	Excellent
Selection Rationale	Impractical for Mach number .6	Selected	Inefficient oversized compressors. Weight penalty.

TABLE 9. ROTOR AND FAN DRIVE DIFFERENCES

	DDA V/STOL Clutch	Tentative X-Wing Requirements
Fan/Rotor Inertia at Speed, $kg \cdot m^2$ ($lb \cdot ft^2$)	22.1 (525)	16,856 (400,000)
Inertia at Clutch, $kg \cdot m^2$ ($lb \cdot ft^2$)	391 (92.7)	3.00 (71.1)
Fan/Rotor Windage Loss, kW (1270 hp)	947 (1270)	$\sim$0
Max Power through Clutch, kW (11,510 hp)	8583 (11,510)	7457 (10,000)
Max Design Torque, n·m (in·lb)	9720 (86,032)	5310 (47,000)

EVALUATION CRITERIA

The evaluation criteria, as approved by the NASA Project Manager are listed in Table 10. The quantitative rotorcraft parameters were calculated by Boeing-Vertol for the average missions, load factors and fuel prices as restated in Table 11.

DOC was selected as the primary criterion because it is considered to be a reliable indicator of the relative economic merits of different systems. Fuel burned can be an important independent criterion under conditions of fuel shortages and allocation quotas. Acquisition cost can be important during periods of high interest and unavailable investment funds.

The qualitative factors were assessed by reviewing the prospective designs with experts in the various disciplines, such as acoustics and reliability and maintainability. "Community acceptance" and "passenger acceptance" refer primarily to far field noise and cabin noise, respectively. Reliability was found to be chiefly a function of the number of propulsion system components (engines, gearboxes, clutches, etc.) "Operability" involves a qualitative assessment of operational suitability and flexibility relative to a variety of missions, including such factors as reverse thrust capability.

TABLE 10. EVALUATION CRITERIA

DOC	Primary Quantitative
Fuel Burned	Secondary Quantitative
Acquisition Cost	Secondary Quantitative
Community Acceptance	Secondary Qualitative
Passenger Acceptance	Secondary Qualitative
Reliability	Secondary Qualitative
Operability	Secondary Qualitative
Program Risk	Secondary Qualitative

TABLE 11. BASELINE MISSIONS FOR ECONOMIC ANALYSIS

	ABC	X-Wing
Ambient Conditions	ISA	ISA
Range, km (nmi)	370 (200)	833 (450)
Cruise Alt, m (ft)	3048 (10000)	9144 (30000)
Load Factor, %	65	85
Fuel Price, \$/l (\$/gal)	.528 (2.00)	594 (2.25)
Annual Utilization, hr	2500	2000

BASELINE SEPARATE ENGINES

Definitions of separate turboshaft and turbofan engines for the Task I rotorcraft were established considering past General Electric experience with fixed and rotary wing aircraft. The turbofan cycles selected were appropriate to the design cruise conditions of the two rotorcraft; the turboshaft cycles were the same for both aircraft. All four powerplants shared a common core design, scaled as necessary for each function.

Turboshaft Engines

The common turboshaft engine selected for the ABC and X-Wing vehicles is an advanced technology engine typical of those under study by General Electric for the next generation of engines in the 3500-4000 kW (approximate 5000 hp) class. The engine features an inlet particle separator; a 1315°C (2400°F) class, 22:1 pressure ratio core with an axi-centrifugal compressor and a 2 stage high pressure turbine; and a 3 stage free power turbine. Performance, weight, and economic data were provided to Boeing Vertol in one engine size, with scaling relationships to cover the expected range of aircraft sizes.

Aircraft incorporating the separate turboshaft and turbofan engines were sized as described above, and the engine sizes required to meet the mission groundrules ("mission size") determined. For both aircraft, the sea level OEI hover power requirement on an ISA +15°C (27°F) day was the determining factor in sizing the turboshaft engines. Table 12 summarizes the performance of the turboshafts which result after scaling into mission size. Note the low part power operation of the engines at the typical flight conditions provided (other than OEI).

The engine weight for the turboshaft was calculated including weights for the inlet particle separator, accessory gearbox and engine accessories. The weights of installation items, including starter, mounts, and inlet and exhaust ducting, were provided by Boeing Vertol. The only transmission element included in the engine weight is a short output shaft at the front of the engine. For the mission sized turboshaft engines, the estimated weights are shown in Table 13. Sketches with leading dimensions of the turboshaft engines are shown in Figures 10 and 11 for the ABC and X-Wing applications, respectively. Engine weight was provided to Boeing Vertol as a function of engine scale factor (where engine scale factor is the ratio of required power or thrust at the limiting condition to that available from the nominal size engines). For moderate variations in engine size, weight may be assumed to vary directly with engine airflow.

Table 13 also shows the turboshaft engine price and maintenance cost estimates in 1981 dollars based on a fleet size of 500 aircraft (1000 engines plus 400 spares). ABC engine maintenance costs are based on a total of 25,000 flight hours and the X-Wing maintenance costs on 20,000 hours, both over a period of ten years. The model used for estimating the maintenance cost is based on actual experience with commercial engines. The engine cost is broken down into major components and then the material cost over the life of the engine is determined considering the expected replacement rate of each individual part. The labor cost is then calculated as a percentage of the material cost for the major components. Finally, the maintenance cost in dollars per engine flight hour is determined by dividing the total material and labor cost by the projected number of flight hours. Engine price and maintenance costs may be scaled to larger or smaller engine sizes by the expression

$$\frac{\text{Price}}{\text{Base Price}} = (\text{Engine Scale Factor})^{0.55}$$

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TABLE 12A. TASK I BASELINE SEPARATE TURBOSHAFT ENGINES

(Mission Size)

SI Units

Vehicle	ABC	X-Wing
Sea Level OEI Hover, ISA +15°C		
Output Power, kW	4080	9570
Inlet Corrected Flow, kg/s	14.9	34.9
T41, °C	1288	1288
Core Pressure Ratio	22.0	22.0
Fuel Flow, kg/h	1010	2360
BSFC, kg/kW·h	.25	.25
Design Cruise, ISA +10°C		
Alt, m	3048	9144
True Airspeed, km/h	463	741
Output Power, kW	1530	270
T41, °C	940	580
Core Pressure Ratio	14.0	6.5
Fuel Flow, kg/h	415	170
BSFC, kg/kW·h	.27	.63
Sea Level Normal Takeoff, ISA		
Output Power, kW	1790	4490
T41, °C	960	980
Fuel Flow, kg/h	550	1340
BSFC, kg/kW·h	.31	.30
Mid Point of Cruise, ISA		
Alt, m	3048	9144
True Airspeed, km/h	463	741
Output Power, kW	1235	275
T41, °C	855	555
Fuel Flow, kg/h	350	170
BSFC, kg/kW·h	.29	.61

TABLE 12B. TASK I BASELINE SEPARATE TURBOSHAFT ENGINES

(Mission Size)

English Units

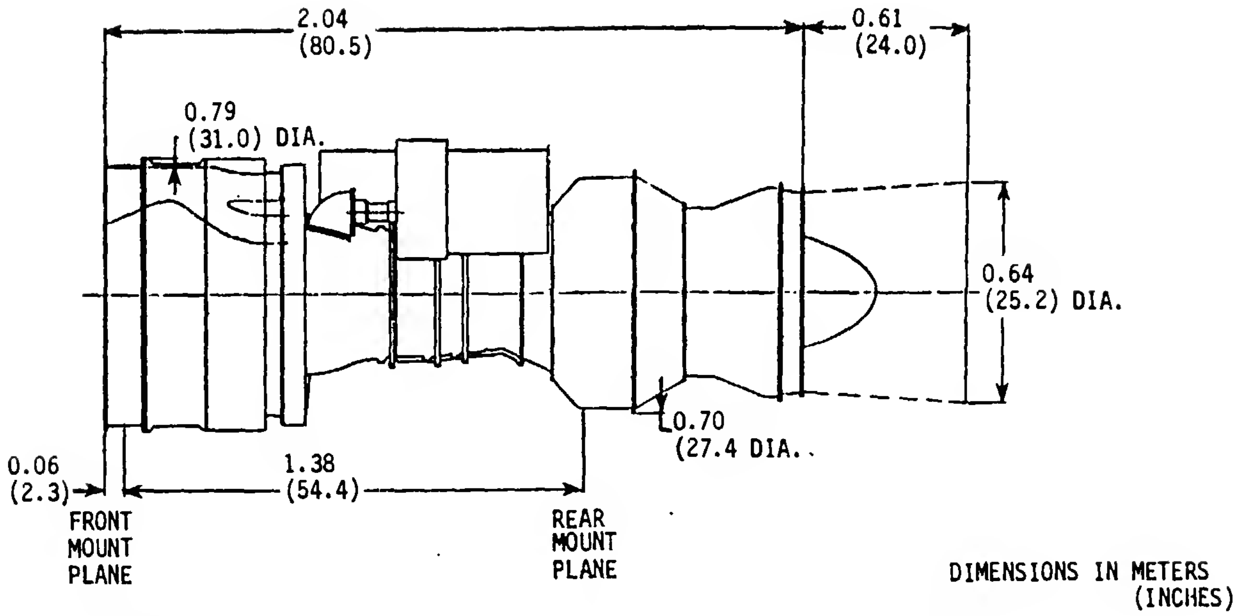
Vehicle	ABC	X-Wing
Sea Level OEI Hover, ISA +27°F		
Output Power, hp	5470	12830
Inlet Corrected Flow, lbm/sec	32.9	77.0
T41, °F	2350	2350
Core Pressure Ratio	22.0	22.0
Fuel Flow, lbm/hr	2230	5200
BSFC, lbm/hp·hr	.41	.41
Design Cruise, ISA +18°F		
Alt, ft	10000	30000
True Airspeed, kt	250	400
Output Power, hp	2050	360
T41, °F	1730	1080
Core Pressure Ratio	14.0	6.5
Fuel Flow, lbm/hr	915	370
BSFC, lbm/hp·hr	.45	1.0
Sea Level Normal Takeoff, ISA		
Output Power, hp	2400	6020
T41, °F	1760	1790
Fuel Flow, lbm/hr	1210	2960
BSFC, lbm/hp·hr	.51	.49
Mid Point of Cruise, ISA		
ALT, ft	10000	30000
True Airspeed, kt	250	400
Output Power, hp	1655	370
T41, °F	1575	1030
Fuel Flow, lbm/hr	775	370
BSFC, lbm/hp·hr	.47	1.0

TABLE 13. TASK I BASELINE SEPARATE TURBOSHAFT ENGINES WEIGHT AND ECONOMIC DATA*

(Mission Size)

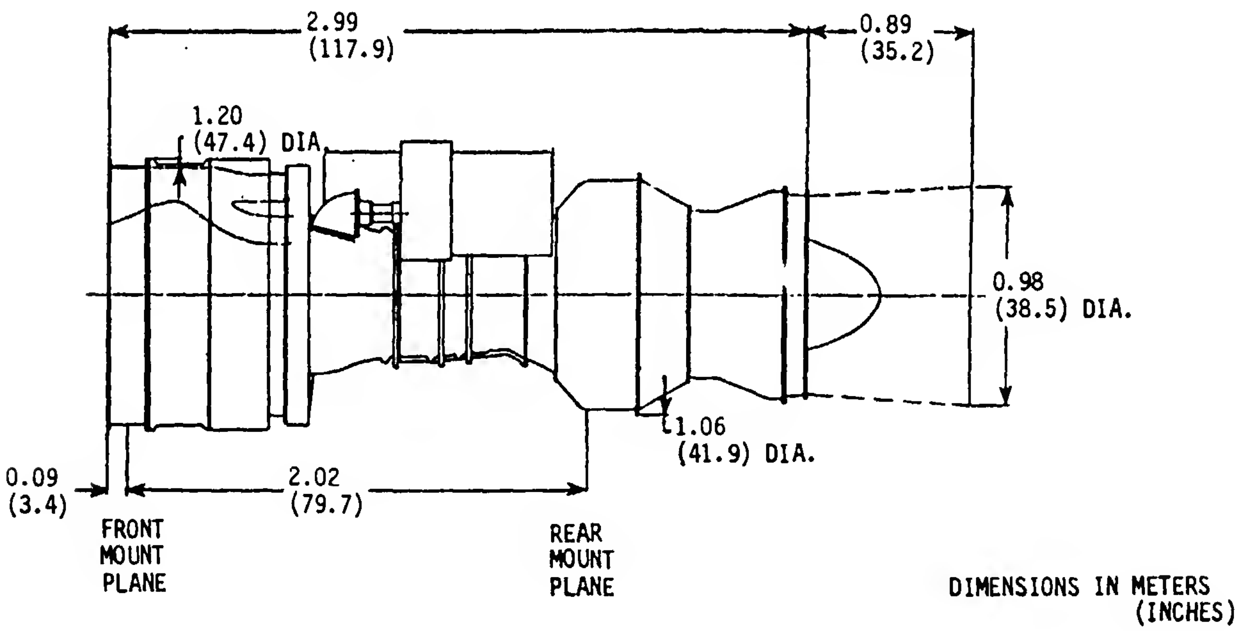
Engine Weight, kg (lbm)	542 (1195)	1304 (2875)
Engine Length, m (in)	2.0 (81)	3.0 (118)
Engine Max. Diameter, m (in)	0.8 (31)	1.2 (48)
Engine Price, $ x 10^{-3}	940	1490
Engine Maintenance Cost, $/hr.	42.80	50.00

*Economic data is furnished by the General Electric Co. for study purposes only in the performance of this contract.



ENGINE WEIGHT = 542 kg (1195 Lbm) EXCLUDING TAILPIPE AND A/C ACCESSORIES

Figure 10. Task I ABC Baseline Separate Turboshaft Engine Mission Size



ENGINE WEIGHT - 1304 kg (2875 Lbm) EXCLUDING TAILPIPE AND A/C ACCESSORIES

Figure 11. Task I X-Wing Baseline Separate Turboshaft Engine Mission Size

BASELINE SEPARATE ENGINES - Continued

Turbofan Engines

ABC Rotorcraft: The relatively low cruise flight speed of the ABC, 463 km/h (250 kt), makes it an appropriate application for a moderately high bypass ratio, low fan pressure ratio turbofan. The optimum fan pressure ratio for this flight speed regime in prior studies has been about 1.4:1. A well documented, advanced technology fan in this range is the fixed pitch, over-the-wing fan designed for the QCSEE (ref. 9) study. This 1.36 pressure ratio fan was scaled to the requirements of the ABC rotorcraft, and matched to the same advanced technology core used in the turboshaft engines. This engine required a 5 stage, direct drive fan turbine. A separate flow exhaust configuration was selected, because the weight and cost penalties of mixed flow exhaust usually outweigh the performance gain at a fan pressure ratio less than 1.4:1.

The ABC separate turbofan engine sketch is shown in Figure 12. The engine weight includes the accessory gearbox with the engine accessories. Only the walls of the bypass ducting and exhaust nozzle are included in the weight, with the weights of the inlet fairing, nacelle, mounting arrangement and aircraft accessories being provided by Boeing Vertol. The weight of the mission sized ABC separate turbofan engine is shown in Table 14. Engine weight scales directly with fan airflow for moderate size variations.

The price and maintenance cost estimates in 1981 dollars of the mission sized ABC turbofan engine, based on a total of 500 aircraft or 1000 engines plus 400 spares, are also shown in Table 14. Engine price and maintenance costs are scaled by (engine scale factor)$^{0.55}$.

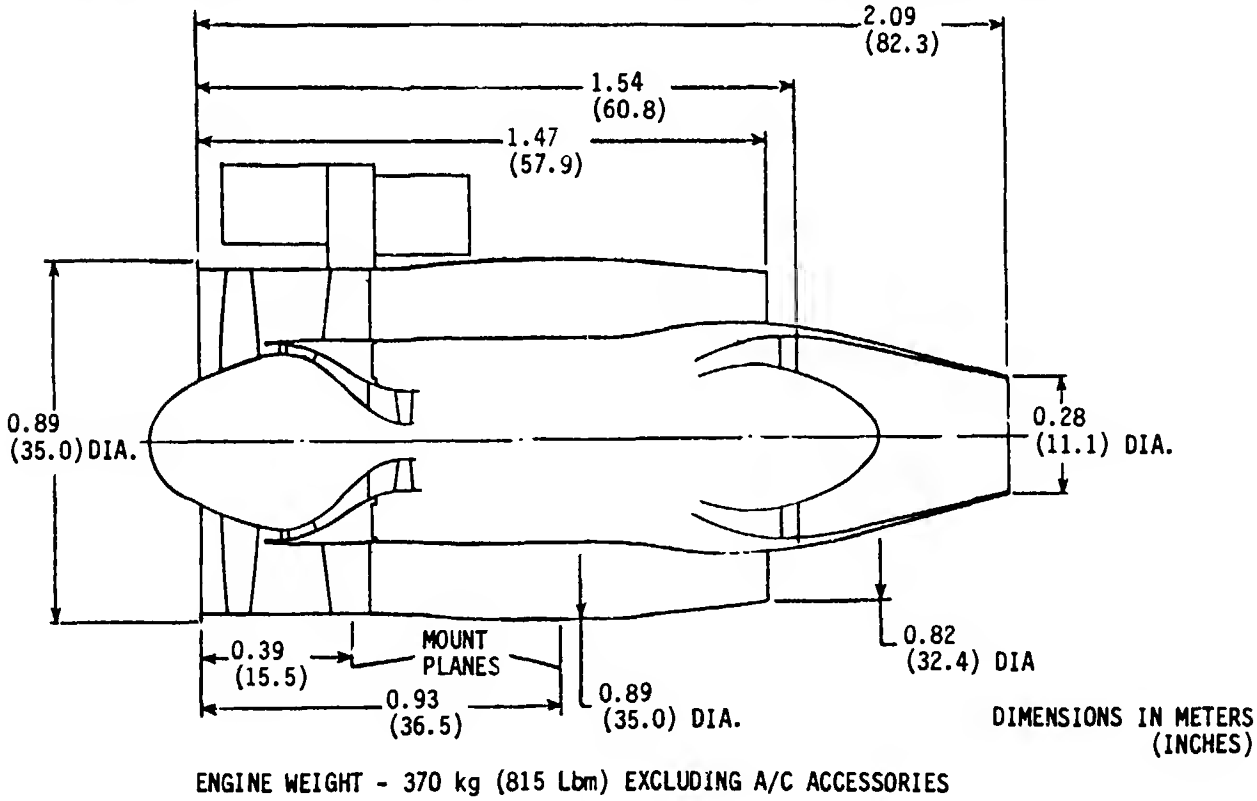


Figure 12. Task I ABC Baseline Separate Turbofan Engine - Mission Size

TABLE 14. TASK I BASELINE SEPARATE TURBOFAN ENGINES WEIGHT AND ECONOMIC DATA*		
	(Mission Size)	
	ABC	X-Wing
Engine Weight, kg (lbm)	370 (815)	880 (1940)
Engine Length, m (in)	1.5 (61)	2.1 (83)
Engine Max. Diameter, m (in)	0.9 (35)	1.3 (51)
Engine Price, \$ x 10^{-3}	790	1360
Engine Maintenance Cost, \$/hr.	25.20	36.00

*Economic data is furnished by the General Electric Co. for study purposes only in the performance of this contract.

TASK I - DEFINITION OF BASELINE AIRCRAFT AND MISSION - Continued

BASELINE SEPARATE ENGINES - Continued

X-Wing Rotorcraft: At the cruise flight speed of the X-Wing, 741 km/h (400 kt), a somewhat higher fan pressure ratio, on the order of 1.7:1 has historically been optimum. In this case an appropriate high technology design was the E^3 fan (ref. 10), at 1.65:1 pressure ratio, which was selected and scaled to match the X-Wing mission. Again, the common advanced technology core was used, this time with a 4 stage, direct drive fan turbine. At a fan pressure ratio of 1.65, mixed flow exhaust was considered to be of sufficient benefit to include in the engine design.

The mission size performance of the separate turbofan engines for both aircraft is summarized in Table 15.

A sketch of the X-Wing separate turbofan engine is shown in Figure 13. The weight includes the same components as the ABC turbofan with the addition of an exhaust mixer for the mixed flow design. Boeing Vertol again provided the weights of the inlet fairing, nacelle, mounting arrangement and aircraft accessories. The weight of the X-Wing separate turbofan engine is shown in Table 14.

The price and maintenance cost in 1981 dollars of the mission sized X-Wing turbofan engine, based again on a 500 aircraft fleet, are shown in Table 14. Engine price and maintenance cost may be scaled by (engine scale factor)$^{0.55}$.

TABLE 15A. TASK I BASELINE SEPARATE TURBOFAN ENGINES		
(Mission Size)		
SI Units		
Vehicle	ABC	X-Wing
Exhaust Configuration	Separate Flow	Mixed Flow
Aero, Design, ISA +10°C		
Alt, m	3048	9144
True Airspeed, km/h	463	741
Thrust, N	9360	14460
Inlet Corrected Flow, kg/s	90	200
Core Corrected Flow, kg/s	7.0	20.5
T41, °C	1260	1260
Aero, Design, ISA +10°C - Continued		
Fan Pressure Ratio	1.36	1.65
Cycle Pressure Ratio	31.3	32.1
Core Pressure Ratio	22.0	22.0
Fuel Flow, kg/h	480	880
TSFC, kg/N·h	.051	.061
Design Cruise, ISA +10°C		
Alt, m	3048	9144
True Airspeed, km/h	463	741
Thrust, N	8290	12820
T41, °C	1190	1190
Fan Pressure Ratio	1.32	1.57
Cycle Pressure Ratio	28.4	29.1
Fuel Flow, kg/h	425	775
TSFC, kg/N·h	.051	.060
Mid Point of Cruise, ISA		
Alt, m	3048	9144
True Airspeed, km/h	463	741
Thrust, N	8600	12390
T41, °C	1160	1130
Fuel Flow, kg/h	435	740
TSFC, kg/N·h	.050	.059
OEI Hover, ISA +15°C		
T41, °C	Idle	Idle
Fuel Flow, kg/h	75	235
Normal Takeoff, ISA		
T41, °C	Idle	Idle
Fuel Flow, kg/h	75	235

TABLE 15B. TASK I BASELINE SEPARATE TURBOFAN ENGINES

(Mission Size)

English Units

Vehicle	ABC	X-Wing
Exhaust Configuration	Separate Flow	Mixed Flow
Aero. Design, ISA +18°C		
Alt, ft	10000	30000
True Airspeed, kt	250	400
Thrust, lbf	2100	3250
Inlet Corrected Flow, lbm/sec	195	440
Core Corrected Flow, lbm/sec	15.5	45.1
T41, °F	2300	2300
Fan Pressure Ratio	1.36	1.65
Cycle Pressure Ratio	31.3	32.1
Core Pressure Ratio	22.0	22.0
Fuel Flow, lbm/hr	1060	1940
TSFC, lbm/lbf·hr	.50	.60
Design Cruise, ISA +18°F		
Alt, ft	10000	30000
True Airspeed, kt	250	400
Thrust, lbf	1860	2880
T41, °F	2180	2180
Fan Pressure Ratio	1.32	1.57
Cycle Pressure Ratio	28.4	29.1
Fuel Flow, lbs/hr	935	1710
TSFC, lbm/lbf·hr	.50	.59
Mid Point of Cruise, ISA		
Alt, ft	10000	30000
True Airspeed, kt	250	400
Thrust, lbf	1930	2785
T41, °F	2130	2060
Fuel Flow, lbm/hr	955	1625
TSFC, lbm/lbf·hr	.49	.58
OEI Hover, ISA +27°F		
T41, °F	Idle	Idle
Fuel Flow, lbm/hr	160	520
Normal Takeoff, ISA		
T41, °F	Idle	Idle
Fuel Flow, lbm/hr	160	520

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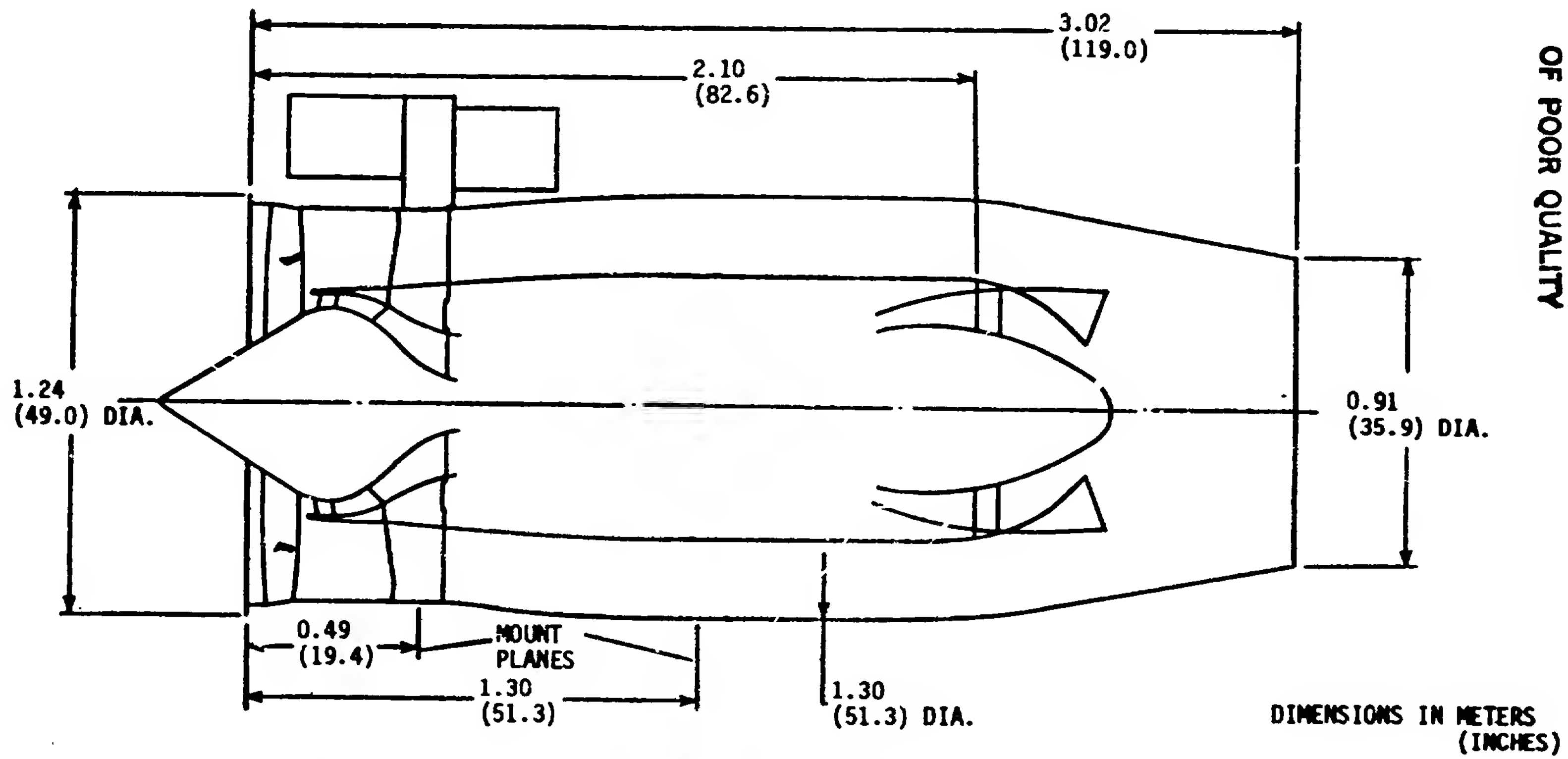

ENGINE WEIGHT = 880 kg (1940 Lbm) EXCLUDING A/C ACCESSORIES

Figure 13. Task X-Wing Baseline Separate Turbofan Engine - Mission Size.

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BASELINE ROTORCRAFT/SEPARATE ENGINES

HESCOMP and VASCOMP computer programs were used to determine sizing and performance data for the ABC and X-Wing separate engine aircraft, respectively. A common, one-engine-inoperative (OEI) criterion was used for both aircraft types, where engines were sized to provide a thrust-to-weight ratio (T/W) of 1.03 at 100% maximum power at sea level, ISA +15°C (27°F).

Baseline ABC Rotorcraft - Separate Engines

The baseline ABC rotorcraft is powered by separate shaft turbine engines and high bypass fan engines. As shown in Figure 14, two shaft turbine engine provide power for the co-axial counter-rotating rotor system and the high bypass fan engines provide thrust for high speed flight.

The two shaft turbines are mounted aft of the rotor above the cabin and drive through over-running clutches to the rotor gearbox. The rotor gearbox has twin inputs to a spiral bevel gear and then torque is transmitted through a compound planetary gear set to provide for further reduction of speed and counter-rotation. The fan engines are mounted on short pylons adjacent to the rotor gearbox. The pylons include inlets and ducting to the shaft turbines as shown in the three-view in Figure 15.

Aircraft fuselage dimensions are based on sizing the passenger cabin to a single aisle, four-abreast seating arrangement, with lavatory and baggage provisions aft. Aircraft dimensional data are summarized in Table 16. The large cabin size accounts for 9.3% of the gross weight. The Aircraft weight breakdown is presented in Table 17. The large rotor weight is due to the complexities of the coaxial hub and the rigid structure of the rotor blades. The engine weights were scaled according to General Electric supplied data.

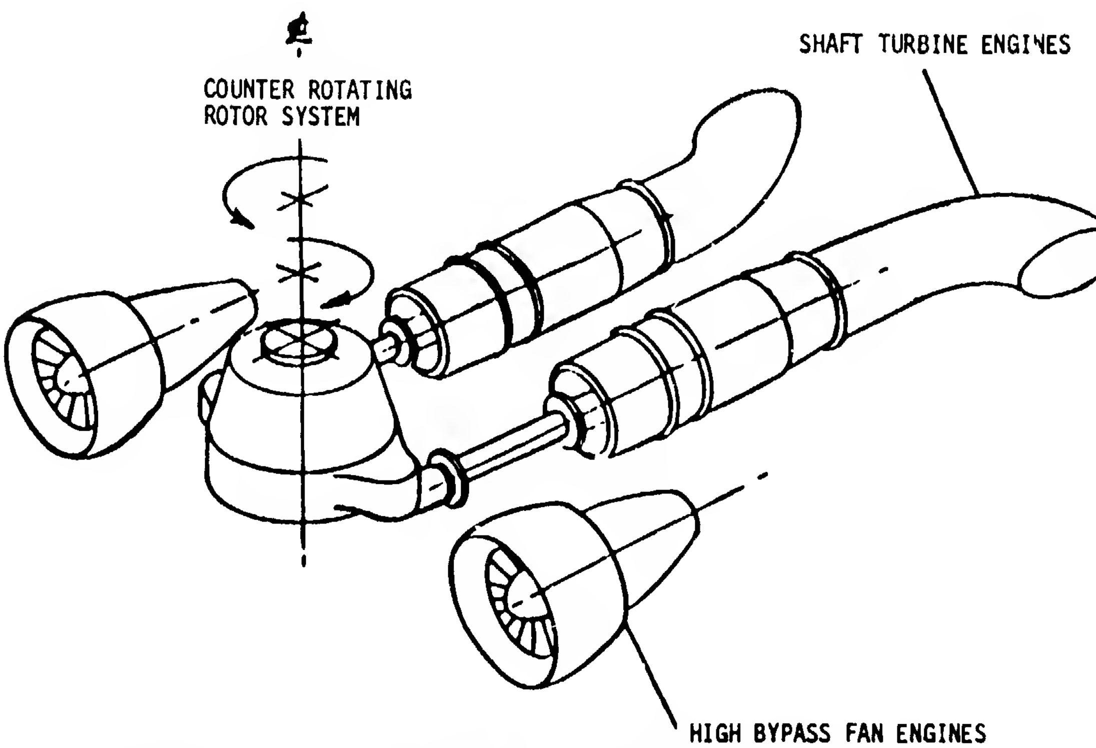
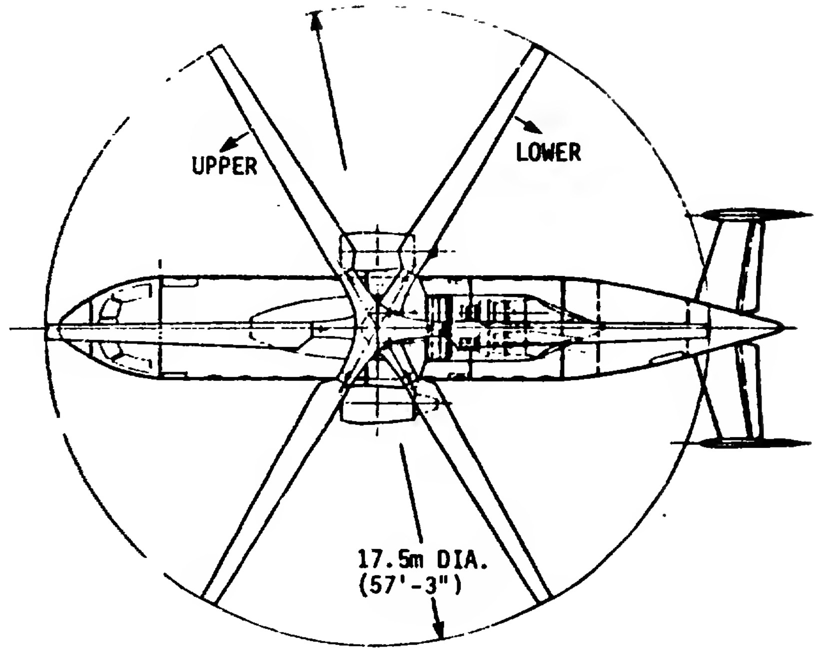
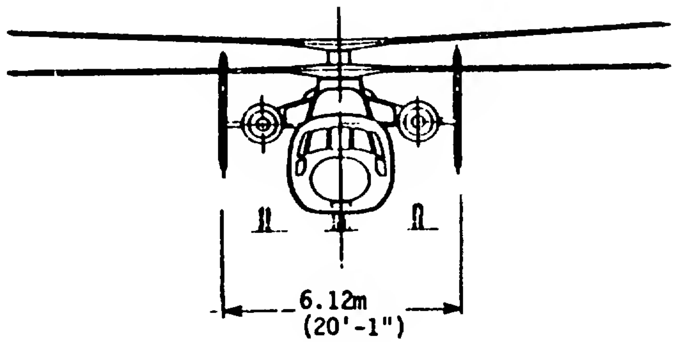


Figure 14. ABC Propulsion System - Separate Lift/Thrust Engines



GROSS WEIGHT	=	17486 kg (38551 lb)
EMPTY WEIGHT	=	10731 kg (23659 lb)
FUEL WEIGHT	=	2024 kg (4462 lb)
INSTALLED HP	=	9461 kw (12688 hp)
INSTALLED THRUST	=	39072 ZN (8784 lb)
ROTOR DIAMETER	=	17.4m (57.2 ft)



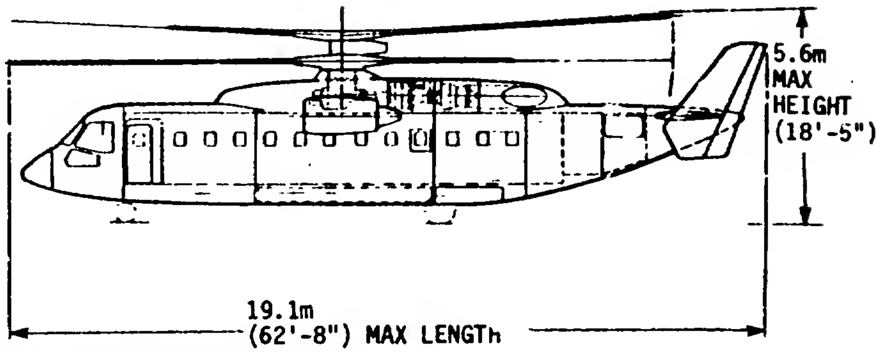


Figure 15. ABC Separate Engine Aircraft

TABLE 16. TASK I ABC AIRCRAFT DESIGN SUMMARY	
	Separate Engine Configuration
Gross Weight, kg (lb)	17486 (38551)
Weight Empty, kg (lb)	10.731 (23659)
Fixed Useful Load, kg (lb)	376 (830)
Payload, kg (lb)	4354 (9600)
Fuel Weight, kg (lb)	2024 (4462)
Fuselage Length, m (ft)	18.6 (60.9)
fuselage Width, m (ft)	2.7 (8.7)
Horizontal Tail:	
Aspect Ratio	5.05
Span, m (ft)	6.0 (19.6)
Thickness/Chord	0.12
Mean Chord, m (ft)	1.2 (3.9)
Vertical Tail:	
Aspect Ratio	1.5
Span, m (ft)	3.6 (11.7)
Thickness/Chord	0.15
Mean Chord, m (ft)	2.4 (7.8)
Main Rotor:	
Diameter, m (ft)	17.4 (57.2)
Solidity	0.1604
Disc Loading, kg/m^2 (lb/ft^2)	73 (15)
Tipspeed, m/s (ft/s)	204 (670)
Aerodynamic Data:	
Total Effective Flatplate Drag, m^2 (ft^2)	2.3 (24.9)
Total Wetted Area, m^2 (ft^2)	167 (1794)
Mean Skin Friction Coeff.	0.01388
Aircraft Efficiency Factor	0.88071

TASK I - DEFINITION OF BASELINE AIRCRAFT AND MISSION - Continued

BASELINE ROTORCRAFT/SEPARATE ENGINES - Continued

Based on the engine sizing criteria, the primary turboshaft engines provide 4731 kW (6344 hp) each and the turbofans provide 19540 N (4392 lb) thrust each at maximum static sea level standard conditions. Table 18 illustrates the drag breakdown for various aircraft components during cruise flight. The thrust-power split is determined from the shaft power required to simultaneously maintain lift during flight and overcome the hub drag, while the fan engines supply the additional thrust necessary to attain cruise speed. The high shaft power requirement results from a combination of the aircraft weight and the large drag associated with the coaxial rotor system.

Fuel is contained in crashworthy underfloor fuel cells. Fuel usage for the design and off-design missions is shown in Table 19. The shaft engines burn the majority of fuel at takeoff since the turbofans operate at flight idle. Climb fuel is low due to the high maximum rate-of-climb capability of the aircraft. The cruise segment constitutes the majority of the fuel burned with similar fuel flows for the fan and shaft engines. Fuel costs are the major contributor to direct operating costs as illustrated in Figure 16. The operating costs attributable to the powerplants are similar in magnitude to the operating costs attributable to the airframe and dynamic systems.

TABLE 17. TASK I - WEIGHT BREAKDOWN	Weight (kg)	Weight (lb)
Body	1633	3600
Rotor	1450	3197
Tail Surfaces	55	121
Tail Rotor	-	-
Landing Gear Group	655	1445
Flight Controls	668	1473
Fixed Equipment	2087	4600
Vibration Absorbers	175	386
Turboshafts or Prop/Shafts		
Engines	1025	2392
Mounts & Pylons	23	52
Firewalls	12	26
Inlets, Cowling, & Exhaust	46	102
Controls	32	70
Starters	76	167
Turbofans or VIGV Fans		
Engines	738	1627
Mounts & Pylons	27	58
Firewalls	10	23
Inlets, Cowling & Exhaust	43	95
Controls	32	70
Starters	51	114
Fuel System	219	482
PTO Gear	111	244
Prop(s) and Installation	-	-
Prop Gear	-	-
Prop Transmission	-	-
Misc. Gears & Shafts	1503	3315
Weight Empty	10731	23659
Crew	327	720
Trapped Liquids & Oil	50	110
Payload	4354	9600
Fuel	2024	4462
Gross Weight	17486	38551

TABLE 18. TASK I ABC DRAG SUMMARY

Component	Effective Flat Plate Area, m^2 (ft^2)
Co-Axial Hub	1.35 (14.57)
Fuselage	.40 (4.30)
Nacelles	.17 (1.84)
Vertical Tail	.16 (1.72)
Pylon	.09 (.96)
Horizontal Tail	.06 (.62)
Miscellaneous	.08 (.90)
Total	2.31 (24.91)

TABLE 19. TASK I - AIRCRAFT FUEL BURNED SUMMARY ABC ROTORCRAFT

	Fuel Burned, kg (lbm) Separate Engines
Design Mission	
Takeoff	57 (125)
Climb	72 (160)
Cruise	1268 (2795)
Reserve	626 (1380)
Total	2023 (4460)
Economic Mission	
Ground Handling and Takeoff	29 (65)
Climb	68 (150)
Cruise	1002 (2210)
Air Maneuver	39 (85)
Descent & Approach	39 (85)
Block Fuel	1177 (2595)

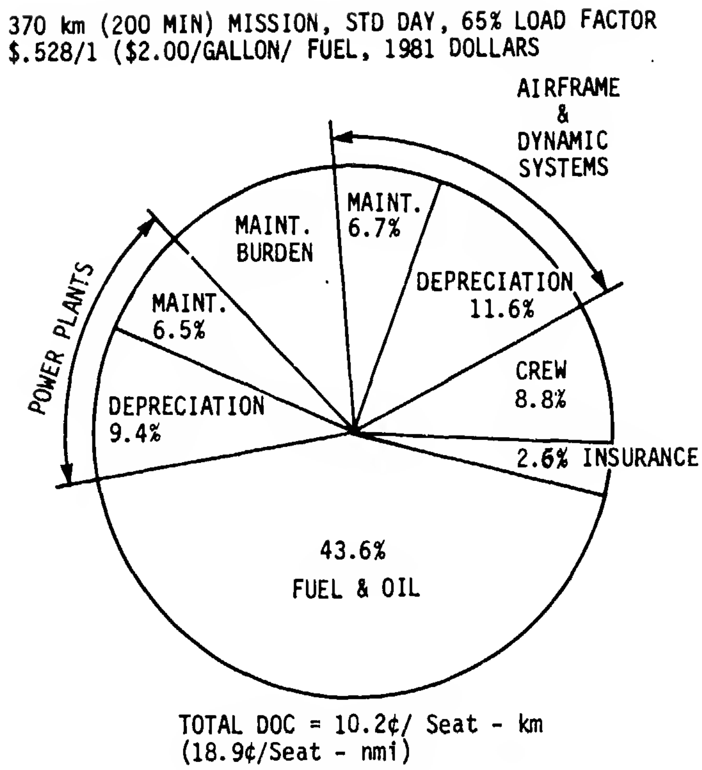


Figure 16. ABC Separate Engine DOC Summary

Baseline X-Wing Rotorcraft - Separate Engines

The baseline X-Wing rotorcraft is powered by two shaft turbines and two thrust engines. As seen in Figure 17, two shaft turbines mounted aft of the main rotor over the cabin drive into the rotor gearbox. Conventional spiral bevel and planetary gear sets reduce the speed and provide power to the rotor shaft. A clutch is provided to disengage the main rotor and Fenestron for conversion to high speed flight. The axial flow compressors are driven by the shaft engines, providing air to the main rotor/wing plenum, through the blade air passages and out to the blades.

Separate high bypass fans are mounted on short pylons from the fuselage structure. The pylons include inlets and ducting to the shaft turbines, as shown in the three-view in Figure 18.

Basic airframe and passenger accommodations follow the same design philosophy as shown previously for the ABC rotorcraft.

Based on the requirements, the aircraft size data were determined and are summarized in Table 20. The fuselage weight reflects cabin size and additional structural strength necessary for pressurization. Table 21 summarizes the aircraft weight distribution. Since little information is available on compressor weight requirements, the compressors are held at a constant weight of 245 kg (540 lb) for all X-wing variants. The flight control weight includes rotor, elevator, and rudder control systems.

The mission requirements dictate an aircraft with a gross weight of 25244 kg (55653 lb) with shaft engines providing 11036 kw (14800 hp) each and fan engines rated at 45425 N (10212 lb) thrust each at sea level static conditions. Since the aircraft climbs and cruises in the fixed wing mode, the shaft engines supply power for the compressors and accessories only. A hub

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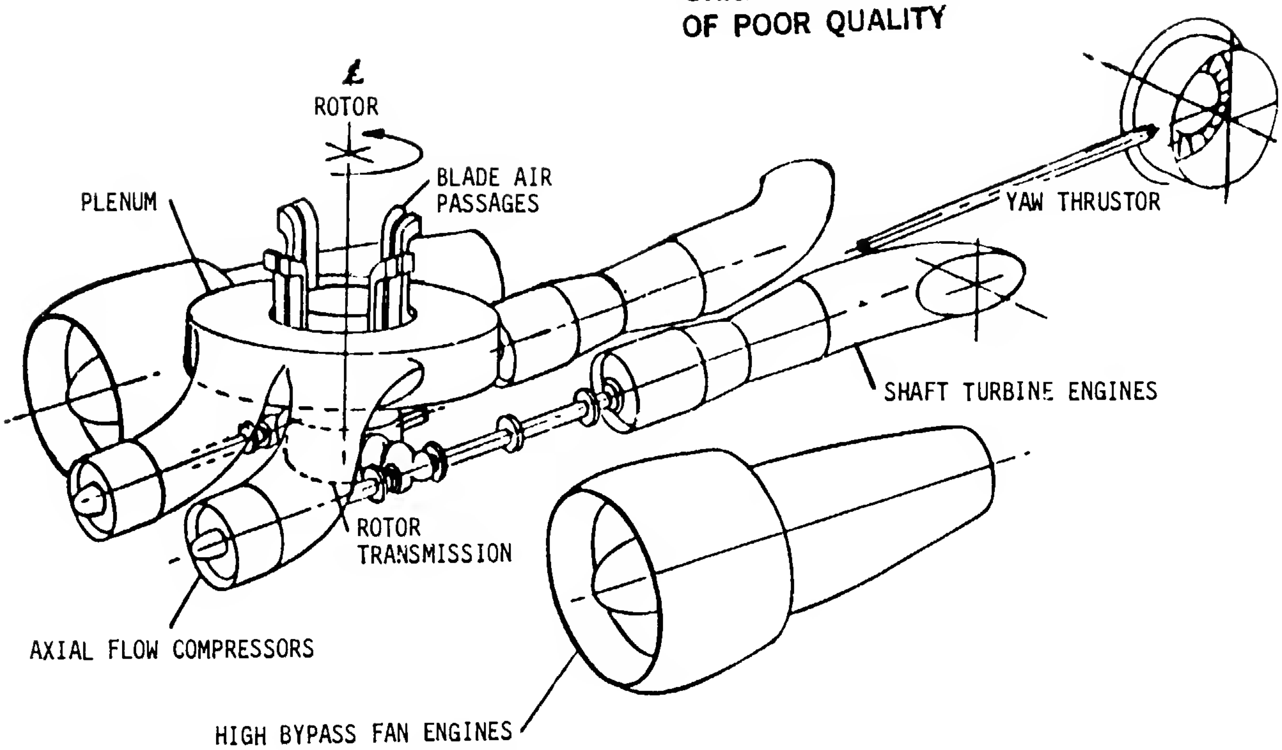

Figure 17. X-Wing Propulsion System - Separate Lift/Thrust Engines

fairing offers a low rotor/wing drag in the fixed wing mode as illustrated in the drag breakdown found in Table 22. Therefore, the shaft power requirements are low throughout the mission except for takeoff, where, alternatively, the thrust required is low. Correspondingly, the mission fuel breakdown, illustrated in Table 23, is primarily due to the fan engines. As illustrated in Figure 19, the fuel usage has a large impact on direct operating costs. Due to the uncommonly high requirements for shaft power and thrust, the power plants represent 18.1% of the total DOC. The aircraft and dynamic systems cost reflect the complexity associated with an X-Wing configuration. The crew, insurance, and maintenance costs are representative for the mission and aircraft utilization under consideration.

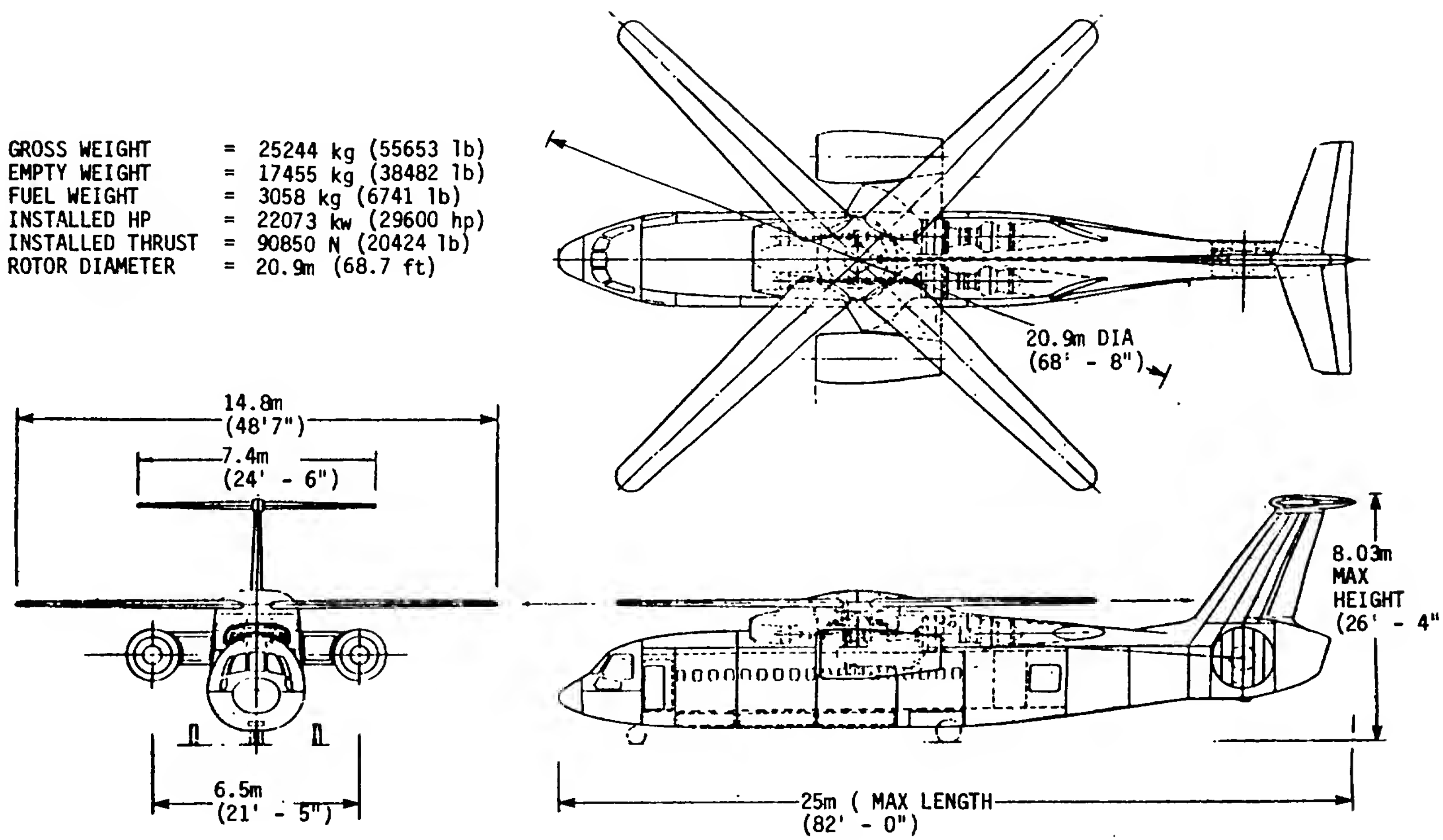

Figure 18. X-Wing Separate Engine Aircraft

TABLE 20. TASK I X-WING AIRCRAFT DESIGN SUMMARY

	Separate Engine Configuration
Gross Weight, kg (lb)	25244 (55653)
Weight Empty, kg (lb)	17455 (38482)
Fixed Useful Load, kg (lb)	376 (830)
Payload, kg (lb)	4354 (9600)
Fuel Weight, kg (lb)	3058 (6741)
Fuselage Length, m (ft)	25 (82)
Fuselage Width, m (ft)	3 (10)
Horizontal Tail:	
Aspect Ratio	4.53
Span, m (ft)	7.9 (25.9)
Thickness/Chord	0.10
Mean Chord, m (ft)	1.7 (5.7)
Vertical Tail:	
Aspect Ratio	1.95
Span, m (ft)	4.63 (15.2)
Thickness/Chord	0.10
Mean Chord, m (ft)	2.3 (7.8)
Main Rotor/Wing:	
Area, m^2 (ft^2)	55.3 (594.8)
Diameter, m (ft)	20.9 (68.7)
Solidity	0.1604
Disc Loading, kg/m^2 (lb/ft^2)	73 (15)
Tipspeed, m/s (ft/s)	198 (650)
Aerodynamic:	
Total Effective Flatplate Drag, m^2 (ft^2)	1.58 (16.96)
Total Wetted Area, m^2 (ft^2)	308 (3315)
Mean Skin Friction Coeff.	0.00512
Aircraft Efficiency Factor	0.8251

TABLE 21. TASK I - X-WING WEIGHT BREAKDOWN

	Weight (kg)	Weight (lb)
Body	2459	5422
Rotor	1842	4062
Tail Surfaces	447	985
Tail Rotor	47	103
Landing Gear Group	947	2087
Flight Controls	1193	2631
Fixed Equipment	2214	4880
Vibration Absorbers	-	-
Turboshafts or Prop/Shafts		
Engines	2607	5747
Mounts & Pylons	57	125
Firewalls	21	46
Inlets, Cowling, & Exhaust	108	237
Controls	32	70
Starters	182	402
Turbofans or VIGV Fans		
Engines	1760	3880
Mounts & Pylons	74	164
Firewalls	16	35
Inlets, Cowling & Exhaust	197	435
Conrols	32	70
Starters	123	272
Fuel System	328	724
PTO Gear	218	481
Prop(s) and Installation	-	-
Prop Gear	-	-
Prop Transmission	-	-
Misc. Gears & Shafts	2306	5084
Compressors	245	540
Weight Empty	17455	38482
Crew	327	720
Trapped Liquids & Oil	50	110
Payload	4354	9600
Fuel	3058	6741
Gross Weight	25244	55653

TABLE 22. TASK I X-WING DRAG SUMMARY

Component	Effective Flat Plate Area, m^2 (ft^2)
Fuselage	.53 (5.74)
Main Rotor (Wings)	.63 (6.75)
Nacelles	.14 (1.50)
Pylon	.07 (.74)
Vertical Tail	.08 (.9)
Horizontal Tail	.08 (.9)
Miscellaneous	.04 (.43)
Total	1.57 (16.96)

TABLE 23. TASK I - AIRCRAFT FUEL BURNED SUMMARY X-WING ROTORCRAFT

	Fuel Burned, kg (lbm) Separate Engines
Design Mission	
Takeoff	204 (450)
Climb	612 (1350)
Cruise	1608 (3545)
Reserve	633 (1395)
Total	3057 (6740)
Economic Mission	
Ground Handling & Takeoff	109 (240)
Climb	515 (1135)
Cruise	1254 (2765)
Air Maneuver	54 (120)
Descent & Approach	274 (605)
Block Fuel	2206 (4865)

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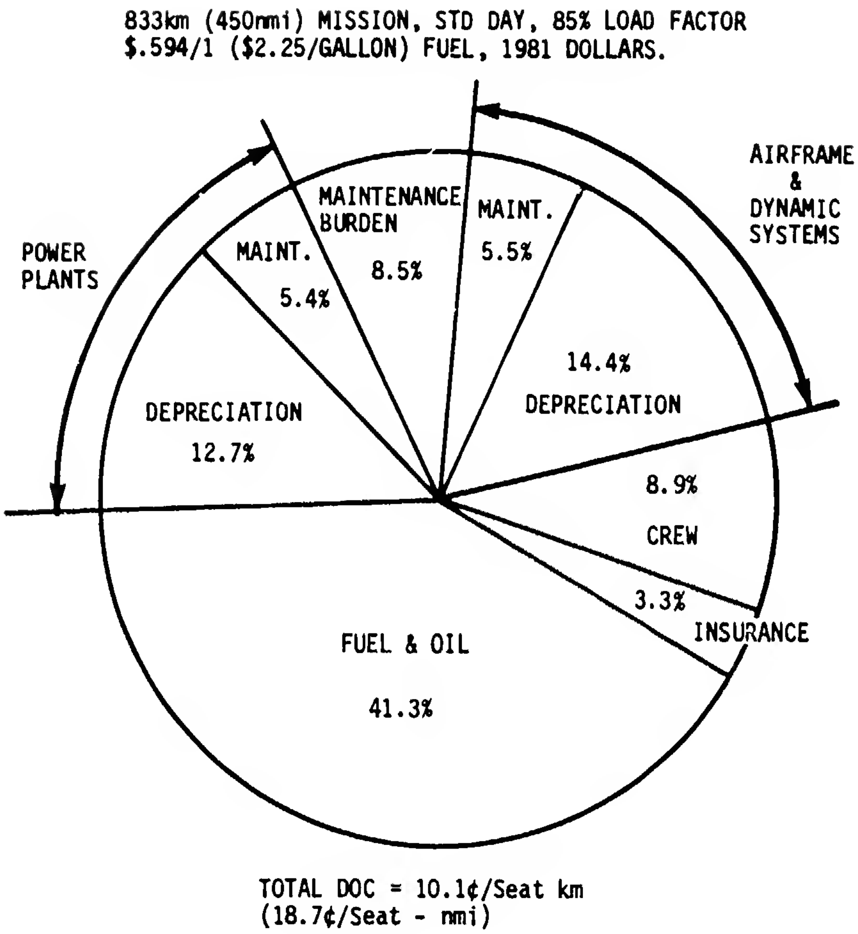

Figure 19. X-Wing Separate Engine DOC Summary

TASK II

BASELINE CONVERTIBLE POWERPLANT SELECTION

TASK II - BASELINE CONVERTIBLE POWERPLANT SELECTION

VARIABLE INLET GUIDE VANE CONVERTIBLE ENGINES

The baseline convertible powerplant type selected for both rotorcraft was the variable inlet guide vane (VIGV) turbofan/turboshaft engine. General Electric's background experience with this type of engine is substantial, including a currently active contract (Contract No. NAS3-22752 with NASA) to demonstrate the concept on a modified TF34 engine.

The principle of operation of the VIGV engine is as follows: Figure 20 shows a schematic comparison of a conventional turbofan and a VIGV fan. In the convertible engine, the airflow through the fan tip is physically isolated from the airflow through the fan hub upstream of the fan rotor, unlike the conventional case where the flow split occurs downstream of the fan rotor. The outer panel (tip) of the fan is provided with variable inlet and exit guide vanes. Closing these vanes allows the fan tip flow, and therefore thrust and the power absorbed by the fan, to be reduced substantially to zero while maintaining constant rotational speed. Because of the isolation of the tip flow, core compressor supercharging is maintained, and the power normally required to drive the fan tip is made available as shaft power. A bevel gear driven output shaft is provided at the front of the engine to deliver power to the rotorcraft transmission. One of the advantages of this system is that a full spectrum of shaft power and thrust combinations are available at partially closed guide vane positions.

In designing VIGV engines for the two rotorcraft, the engine cycles were made as similar to the separate engine cycles as was practical. One important difference between conventional turbofan engines and VIGV fan/shaft engines concerns flow matching between the fan and the core. In

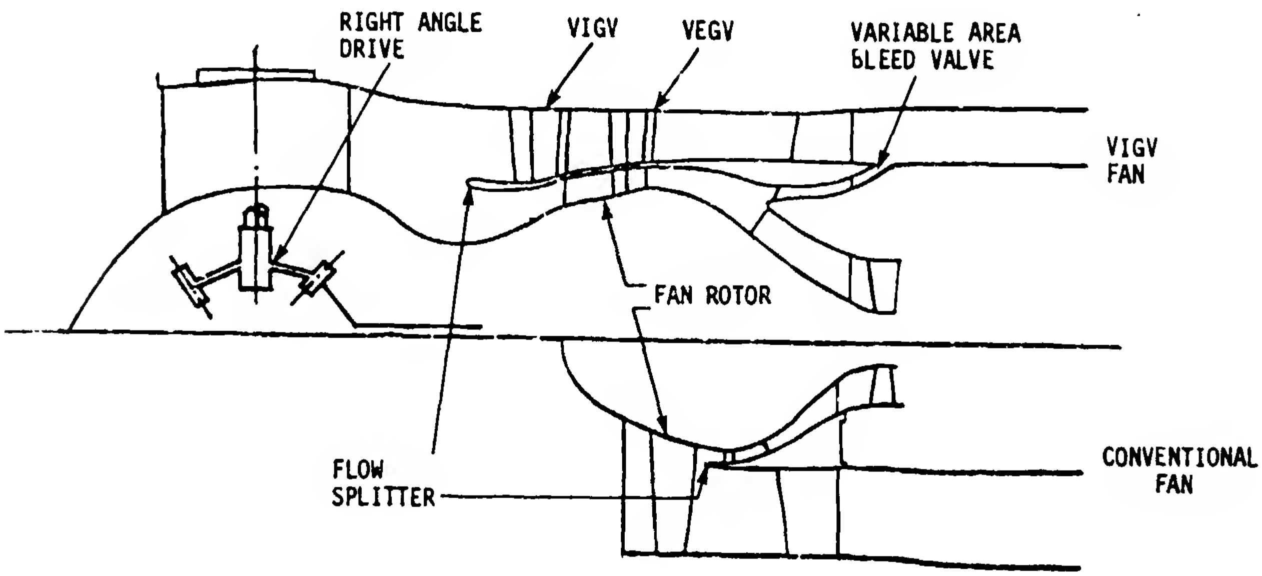

Figure 20. Comparison of VIGV and Conventional Fan Designs

VARIABLE INLET GUIDE VANE CONVERTIBLE ENGINES - Continued

the conventional turbofan, the fan and core are aerodynamically coupled; fan rotor speed and bypass ratio are determined by thermodynamic constraints. In the case of the convertible engine fan, a fan rotor speed is in general imposed on the engine by the rotorcraft control system. This combines with the physical isolation of the fan hub flow to create a flow matching problem between the fan hub exit and the core inlet, which can easily lead to fan hub stall. For this reasons, a variable area bleed valve is provided between the fan exit and core inlet. The valve exhausts into the bypass duct.

ABC Rotorcraft

The design of a convertible engine is in general a compromise between conflicting requirements. Good takeoff performance in the turboshaft mode dictates a large core size and a low exhaust pressure (i.e., extracting the maximum amount of work from the turbine and minimizing residual thrust). Optimum cruise performance in the turbofan mode, however, would occur at a relatively smaller core size (high bypass ratio) and a higher core exhaust pressure. Further compromise is required in the case of the ABC by the output speed required by the rotor system. As mentioned in the Aircraft Design and Sizing Procedure sections (page 12), rotor speed is reduced at high flight speed to maintain a constant advancing blade tip Mach number. This results in the fan speed schedule of Figure 21. One result of this schedule is that fan corrected speed is 15% higher at the ISA +15°C (27°F) sea level hover condition than at the ISA +10°C (18°F) cruise condition at 3048 m (10000 ft).

The ABC baseline convertible engine was designed around the same (scaled) core as the Task I engines. Certain operating limits at the sea level, ISA +15°C (27°F) OEI hover condition were selected a priori, as follows:

Fan Corrected Speed	110% of design
Turbine Inlet Temperature	1288°C (2350°F)
Core Compressor Speed	106% of design

As in the case of the separate turboshaft engine, the OEI hover requirement was the determining factor in engine sizing. The core was sized, subject to the foregoing limits, to provide the same takeoff power as the separate turboshaft engine, and to also provide the additional power absorbed by the fan with maximum VIGV closure. This fan "windage" loss was modeled as a function of fan blade dimensions and speed as (ref. 11)

$$P = (K)\ (r_T{}^4 - r_H{}^4)\ (Cav)\ (Nb)\ (\rho)\ (\omega^3)$$

where

P = Power abosrbed, kW (hp)

r_T = Blade tip radius, outer panel, m (in)

r_H = Blade hub radius, outer panel, m (in)

Cav = Average blade chord, outer panel, m (in)

Nb = Number of blades

ρ = Air density, kg/m^3 (lbm/in^3)

ω = Rotational speed, rad/s (rpm)

K = 3.86×10^{-9} (1.74×10^{-15})

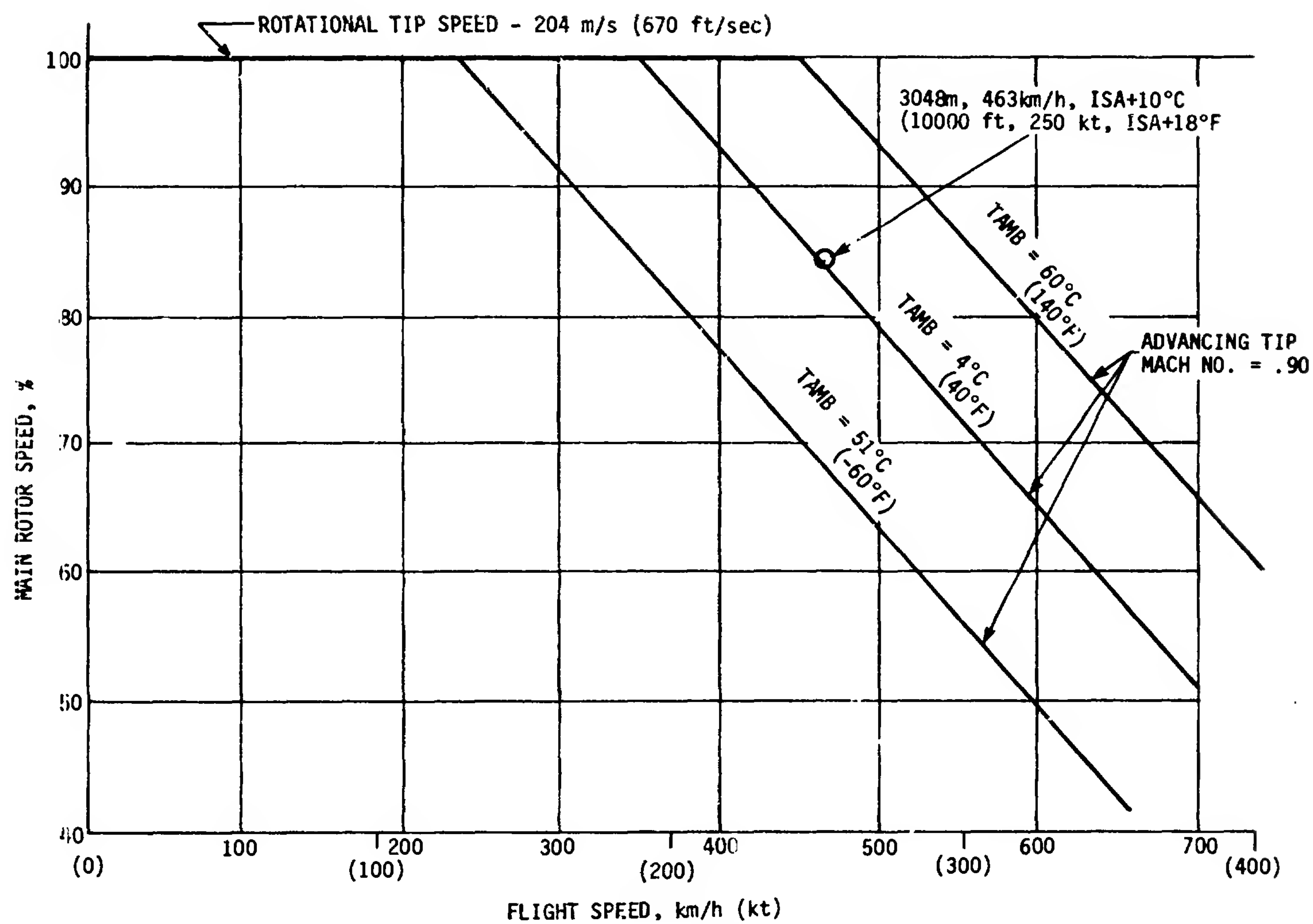

Figure 21. ABC Rotor Speed Schedule

VARIABLE INLET GUIDE VANE CONVERTIBLE ENGINES - Continued

The core exhaust nozzle pressure ratio, PT8/PAMB, was set at a value of 1.18 at OEI hover, this being a compromise between the requirements of a turboshaft and a turbofan engine. Normally, residual thrust for a turboshaft engine is minimized by setting PT8/PAMB as low as possible, which in turn maximizes output power. (For reference, PT8/PAMB for the separate turboshaft engine at OEI hover is 1.025). Optimum SFC for a separate exhaust turbofan, on the other hand, results when the core residual thrust is a moderate percentage of the total. The TF34, for example, has 20% of total thrust produced by the core (at static conditions) at a core nozzle PT8/PAMB of 1.35.

The bleed valve between the fan hub and the core compressor can, if properly designed, serve as an inlet particle separator, reducing the risk of foreign object damage (FOD) to the core. The flowpath through the fan hub is contoured such that the inertia of large objects entrained in the airflow will carry them into the annular bleed duct (see Figure 22). To provide this capability at OEI hover, the fan hub was sized to allow 10% of its airflow to be bled into the bypass duct.

For the fan design, a 1.36 fan pressure ratio, separate exhaust flow configuration was selected for commonality with the Task I turbofan cycle. This fan was sized to provide the same thrust at 3048 m, 463 km/h (10,000 ft, 250 kt) as the Task I turbofan engine, while operating at the corrected speed dictated by the speed schedule of Figure 21. At this condition, the fan and core were matched such that, with fan VIGV's fully open, the engine simultaneously produced the same output power as the Task I turboshaft, and the same thrust as the turbofan. A 5-stage fan drive turbine was required.

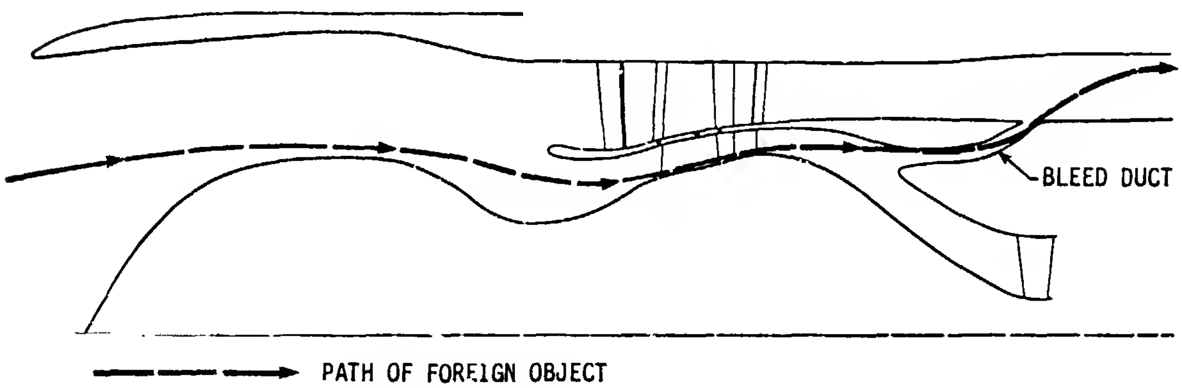

Figure 22. Particle Separation Function of Bleed Duct

VARIABLE INLET GUIDE VANE CONVERTIBLE ENGINES - Continued

A preliminary design of a fan blade with splitter was carried out to predict fan performance. The presence of the splitter gives the designer the opportunity to use different airfoil shapes than he might for a continuous blade, and alters the performance characteristics of the stage. (For example, fan hub pressure ratio trends with wheel speed are different with and without the splitter). Table 23 compares the fan blade designs of the Task I and Task II engines.

TABLE 23A. FAN BLADE COMPARISON - ABC

SI Units

Parameter	Task I Separate Turbofan	Task II VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, m/s	358	317
Corrected Hub Speed, $UH/\sqrt{\theta}$, m/s	151	184
Overall Radius Ratio, r_H/r_T	.42	.58
Bypass Ratio	8.5	3.8
Tip Pressure Ratio	1.36	1.36
Hub Pressure Ratio	1.43	1.37
Tip Specific Flow, $W\sqrt{\theta}/\delta A$, $kg/s\cdot m^2$	-	205
Hub Specific Flow, $W\sqrt{\theta}/\delta A$, $kg/s\cdot m^2$	-	147
Overall Specific Flow, $W\sqrt{\theta}/\delta A$, $kg/s\cdot m^2$	194	181
Tip Efficiency	.865	.870
Hub Efficiency	.780	.832

TABLE 23B. FAN BLADE COMPARISON - ABC

English Units

Parameter	Task I Separate Turbofan	Task II VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, ft/sec	1175	1040
Corrected HUB Speed, $UH\sqrt{\theta}$, ft/sec	495	603
Overall Radius Ratio, r_H/r_T	.42	.58
Bypass Ratio	8.5	3.8
Tip Pressure Ratio	1.36	1.36
Hub Pressure Ratio	1.43	1.37
Tip Specific Flow, $W\sqrt{\theta}/\delta A$, $lbm/sec\cdot ft^2$	-	42.0
Hub Specific Flow, $W\sqrt{\theta}/\delta A$, $lbm/sec\cdot ft^2$	-	30.2
Overall Specific Flow, $W\sqrt{\theta}/\delta A$, $lbm/sec\cdot ft^2$	39.8	37.1
Tip Efficiency	.865	.870
Hub Efficiency	.780	.832

The foregoing unique design features of the convertible engine make the mechanical design of the forward part of the engine more complex than a conventional turbofan. The front frame, in addition to the normal functions of providing the main engine mounts and forward bearing supports for both the high and low pressure rotors, supports the splitter aft of the fan rotor and also incorporates the scavenge air bleed valve. The right angle drive gearbox for shaft power takeoff is supported by four struts to the outer casing. Two struts are thicker than the others to allow for passage of the output shaft for either a right or left hand engine. The shaft extension from the low pressure turbine shaft to the gearbox is splined at the rear and has a bearing in the gearbox. The output shaft from the gearbox is connected to the aircraft shafting at the outside of the outer casing of the engine.

VARIABLE INLET GUIDE VANE CONVERTIBLE ENGINES - Continued

The fan IGV's and EGV's are structural as well as aerodynamic components. The IGV struts support the forward part of the splitter and the EGV struts support the inner flowpath through the fan hub EGV's. The variable flaps on the IGV's and EGV's require additional actuation components, and add to the complexity of the engine control system.

Prices for the convertible engines were established consistently with the separate engines. Costs were estimated for each component scaled to the proper flow size and configuration. To account for the features unique to the convertible engine configuration the following additional items were included in the total engine price:

- Cost of two actuating systems for fan IGV and OGV
- Cost of the static splitter in the flowpath
- Cost of the bleed valve and associated hardware

In addition, the overall cost of the engine was increased by a fixed percentage to compensate for the increased complexity in the control system, torque measuring system and the lube system. This adder also covers items such as the air/oil cooler, 90° gear drive, anti-icing provision, containment shield and implementation of structural requirements unique to commercial engines. The actual figure used is based on the results of a comprehensive study of the T700-GE-700 Booster Engine conducted under Army Contract DAAK51-78-C-0002.

Engine maintenance costs for the convertible engines were calculated by the same methods employed for the separate engines.

Engine performance, weight, and economic data were provided to Boeing Vertol, who repeated the mission analysis work with the convertible engine as powerplant. The performance of the engine after scaling into the resized aircraft is summarized in Table 24 for several important flight conditions. Table 25 provides the resulting weight and economic data for the mission size VIGV engine, with the shaft power takeoff (PTO) gearing and shafting shown separately. Figure 23 is a sketch of the ABC baseline convertible engine with important dimensions shown.

TABLE 24A. TASK II ABC BASELINE VIGV CONVERTIBLE ENGINE

(Mission Size)

SI Units

Condition	OEI Hover ISA +15°C	Normal Takeoff ISA	Design Cruise ISA +10°C	Mid Cruise ISA
Altitude, m	0	0	3048	3048
Flight Speed, km/h	0	0	463	463
Output Power, kW	3890	1690	1340	1270
Fan Windage, kW	390	410	-	-
Thrust, N	4500	2660	7985	7450
Fuel Flow, kg/h	1200	750	745	695
T41, °C	1288	1030	1120	1060
Fan Pressure Ratio	-	-	1.33	1.31
Cycle Pressure Ratio	25.6	18.7	22.3	21.6
Core Pressure Ratio	18.5	13.2	17.0	16.7
Inlet Corrected Flow, kg/s	19.8	20.1	85.3	83.9
Core Corrected Flow, kg/s	13.6	10.5	12.8	12.6
Bypass Ratio	-	-	3.9	3.9
Fan Hub Exit Bleed, %	10	31	8	9
Fan IGV Position	Full Closed	Full Closed	Open* 2°	Open* 1°
Output Shaft Speed, %	100	100	84.5	81.7
Corrected Fan Speed, %	110	113	95.6	94.1
Corrected Core Speed, %	106	92	95.8	95.4

TABLE 24B. TASK II ABC BASELINE VIGV CONVERTIBLE ENGINE

(Mission Size)

English Units

Condition	OEI Hover ISA +27°C	Normal Takeoff ISA	Design Cruise ISA +18°F	Mid Cruise ISA
Altitude, ft	0	0	10000	10000
Flight Speed, kt	0	0	250	250
Output Power, hp	5210	2270	1790	1700
Fan Windage, hp	530	550	-	-
Thrust, lbf	1010	600	1795	1675
Fuel Flow, lbm/hr	2640	1650	1640	1535
T41, °F	2350	1890	2045	1935
Fan Pressure Ratio	-	-	1.33	1.31
Cycle Pressure Ratio	25.6	18.7	22.3	21.6
Core Pressure Ratio	18.5	13.2	17.0	16.7
Inlet Corrected Flow, lbm/sec	43.6	44.4	188	185
Core Corrected Flow, lbm/sec	30.0	23.1	28.2	27.7
Bypass Ratio	-	-	3.9	3.9
Fan Hub Exit Bleed, %	10	31	8	9
Fan IGV Position	Full Closed	Full Closed	Open* 2°	Open* 1°
Output Shaft Speed, %	100	100	84.5	81.7
Corrected Fan Speed, %	110	113	95.6	94.1
Corrected Core Speed, %	106	92	95.8	95.4

*"Open" in this context implies open beyond the design, "Full Open" position

TABLE 25. TASK II BASELINE CONVERTIBLE ENGINES WEIGHT AND ECONOMIC DATA*

(Mission Size)

	ABC	X-Wing
Engine Weight w/o PTO, kg (lbm)	703 (1550)	1190 (2625)
Weight of PTO Gear & Shafting, kg (lbm)	79 (175)	147 (325)
Engine Length, m (in)	3.6 (141)	3.9 (154)
Engine max. diameter, m (in)	1.1 (43)	1.4 (55)
Engine Price w/o PTO, $ x 10^{-3}	1530	2220
Price of PTO Gear & Shafting, $ x 10^{-3}	24	49
Engine Maintenance Cost w/o PTO, $/hr	54.00	66.70
Maint. Cost of PTO Gear & Shafting, $/hr	1.25	2.30

*Economic data is furnished by the General Electric Co. for study purposes only in the performance of this contract.

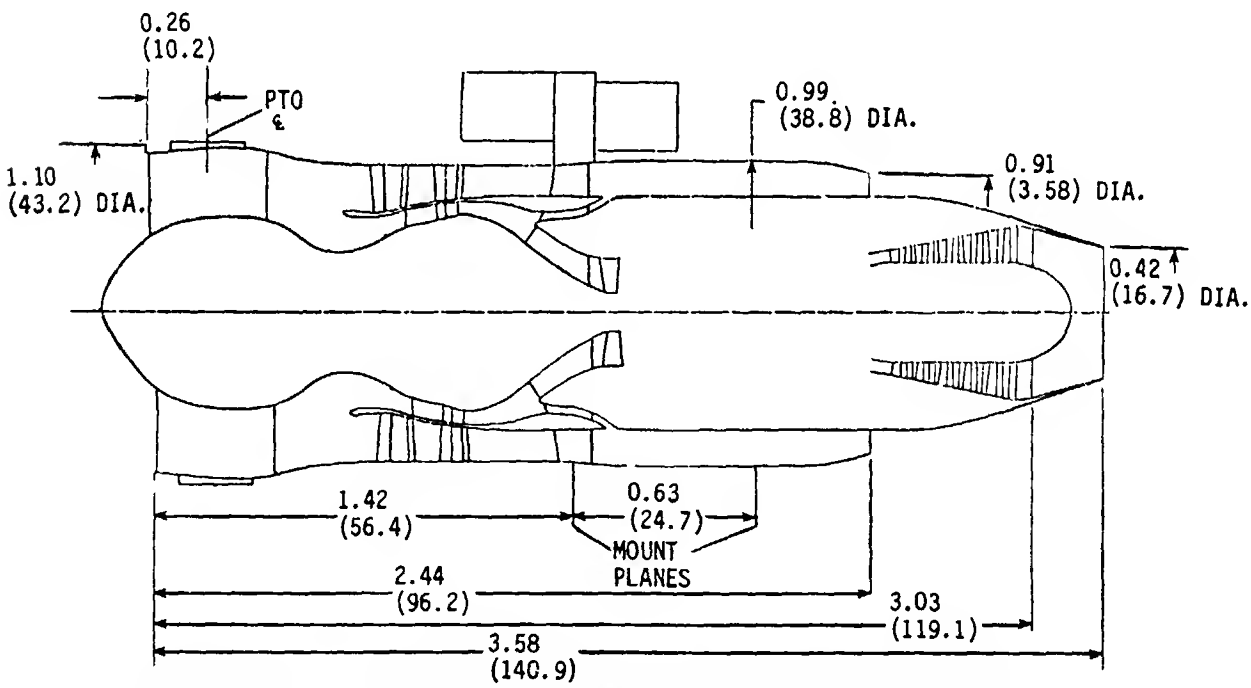

Figure 23. Task II ABC VIGV Convertible Baseline Engine - Mission Size

VARIABLE INLET GUIDE VANE CONVERTIBLE ENGINES - Continued

X-Wing Rotorcraft

The baseline convertible engine for the X-Wing was designed with a 1.65 pressure ratio fan and mixed flow exhaust, to provide as direct a comparison as possible to the Task 1 fan engine. Based on the large core size of the X-Wing Task I turboshaft engine, and the anticipated equally large convertible engine core, a decision was made to design this VIGV engine with an all axial compressor in place of the axi-centrifugal compressor. The compressor and other appropriate core features were scaled from the E^3 design. (NASA-GE Energy Efficient Engine, ref. 10.)

The compromises involved in the design of a VIGV engine for the X-Wing rotorcraft were less severe than in the case of the ABC. Output shaft speed, rather than being reduced for high flight speeds, was held constant in order to assure adequate performance of the circulation control bleed compressors. This leads to an 8% reduction in fan corrected speed between design cruise and OEI hover.

The mixed flow exhaust configuration meant core exhaust area was less of a compromise, also. At the hover (turboshaft mode) condition, the core exhaust area is the area of the core side of the mixer, which is larger than the core nozzle area of a separate flow engine of the same bypass ratio.

As in the case of the ABC, the core was sized to provide the power required by the Task I rotorcraft, plus the power absorbed by the fan outer panel. A 3 stage low pressure turbine was found to be adequate. Limits observed at hover were:

Turbine Inlet Temperature	1288°C (2350°F)
Core Compressor Speed	106% of design

The areas in the exhaust mixer were set to give good mixing performance in the fan mode at cruise. The resulting value of PT8/PAMB at hover was 1.23. Again, a much lower value would be better in terms of maximizing output horsepower, but this is a compromise required by the convertible engine concept.

Although the bleed valve and flowpath between the fan and core were contoured with FOD separation in mind, it was not considered necessary to provide the excess fan hub flow for separation at OEI for such a large core engine. Thus the fan hub was sized for zero bleed at OEI. At normal takeoff power levels, the bleed required for flow matching is more than adequate for FOD separation.

The fan tip was sized at 100% corrected speed with fully open VIGV's to provide the same thrust at end of climb at 9144 m, 654 km/h (30000 ft, 353 kt) as the Task I turbofan engine, and matched with the core to also provide the aircraft bleed compressor power requirement.

A comparison of the Task I and Task II fan designs is shown in Table 26.

Engine performance in mission size is provided in Table 27.

A sketch of the VIGV convertible baseline X-Wing engine is shown in Figure 24. The weight includes the same components as the ABC VIGV convertible engine with the addition of an exhaust mixer for the mixed flow design. Mission size weight and economic data were shown in Table 25.

TABLE 26A. FAN AERO DESIGN COMPARISON - X-WING		
SI Units		
Parameter	Task I Separate Turbofan	Task II VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, m/s	412	420
Corrected Hub Speed, $UH/\sqrt{\theta}$, m/s	144.8	192
Overall Radius Ratio, r_H/r_T	.35	.45
Bypass Ratio	6.2	2.8
Tip Pressure Ratio	1.65	1.65
Hub Pressure Ratio	1.47	1.47
Tip Specific Flow, $W\sqrt{\theta/\delta A}$, $kg/s{\cdot}m^2$	-	203
Hub Specific Flow, $W\sqrt{\theta/\delta A}$, $kg/s{\cdot}m^2$	-	157
Overall Specific Flow, $W\sqrt{\theta/\delta A}$, $kg/s{\cdot}m^2$	210	183
Tip Efficiency	.880	.868
Hub Efficiency	.884	.885

TABLE 26B. FAN AERO DESIGN COMPARISON - X-WING		
English Units		
Parameter	Task I Separate Turbofan	Task II VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, ft/sec	1350	1380
Corrected Hub Speed, $UH\sqrt{\theta}$, ft/sec	475	630
Overall Radius Ratio, r_H/r_T	.35	.45
Bypass Ratio	6.2	2.8
Tip Pressure Ratio	1.65	1.65
Hub Pressure Ratio	1.47	1.47
Tip Specific Flow, $W\sqrt{\theta/\delta A}$, $lbm/sec{\cdot}ft^2$	-	41.5
Hub Specific Flow, $W\sqrt{\theta/\delta A}$, $lbm/sec{\cdot}ft^2$	-	32.2
Overall Specific Flow, $W\sqrt{\theta/\delta A}$, $lbm/sec{\cdot}ft^2$	43	37.5
Tip Efficiency	.880	.868
Hub Efficiency	.884	.885

TABLE 27A. TASK II X-WING BASELINE VIGV CONVERTIBLE ENGINE

(Mission Size)

SI Units

Condition	OEI Hover ISA +15°C	Normal Takeoff ISA	Design Cruise ISA +10°C	Mid Cruise ISA
Altitude, m	0	0	9144	9144
Flight Speed, km/h	0	0	741	741
Output Power, kW	8050	3780	251	242
Fan Windage, kW	790	830	-	-
Thrust, N	11430	6490	11490	11340
Fuel Flow, kg/h	2590	830	840	1010
T41, °C	1288	1000	1015	965
Fan Pressure Ratio	-	-	1.59	1.58
Cycle Pressure Ratio	26.5	19.1	24.1	24.0
Core Pressure Ratio	19.6	13.7	16.9	16.6
Inlet Corrected Flow, kg/s	38.7	39.7	155	154
Core Corrected Flow, kg/s	30.2	22.9	26.8	26.4
Bypass Ratio	-	-	2.7	2.6
Fan Hub Exit Bleed, %	0	24	2	16
Fan IGV Position	Full Closed	Full Closed	Closed 7°	Closed 12°
Output Shaft Speed, %	100	100	100	100
Corrected Fan Speed, %	91.7	94.1	99.1	101.1
Corrected Core Speed, %	98.1	92.7	95.6	95.4

TABLE 27B. TASK II X-WING BASELINE VIGV CONVERTIBLE ENGINE

(Mission Size)

English Units

Condition	OEI Hover ISA +27°F	Normal Takeoff ISA	Design Cruise ISA +18°F	Mid Cruise ISA
Altitude, ft	0	0	30000	30000
Flight Speed, kt	0	0	400	400
Output Power, hp	10800	5070	335	325
Fan Windage, hp	1060	1115	-	-
Thrust, lbf	2570	1460	2580	2550
Fuel Flow, lbm/hr	5700	3420	1830	1790
T41, °F	2350	1835	1860	1770
Fan Pressure Ratio	-	-	1.59	1.58
Cycle Pressure Ratio	26.5	19.1	24.1	24.0
Core Pressure Ratio	19.6	13.7	16.9	16.6
Inet Corrected Flow, lbm/sec	85.3	87.6	342	340
Core Corrected Flow, lbm/sec	66.5	50.4	59.0	58.2
Bypass Ratio	-	-	2.7	2.6
Fan Hub Exit Bleed, %	0	24	2	16
Fan IGV Position	Full Closed	Full Closed	Closed 7°	Closed 12°
Output Shaft Speed, %	100	100	100	100
Corrected Fan Speed, %	91.7	94.1	99.1	101.1
Corrected Core Speed, %	98.1	92.7	95.6	95.4

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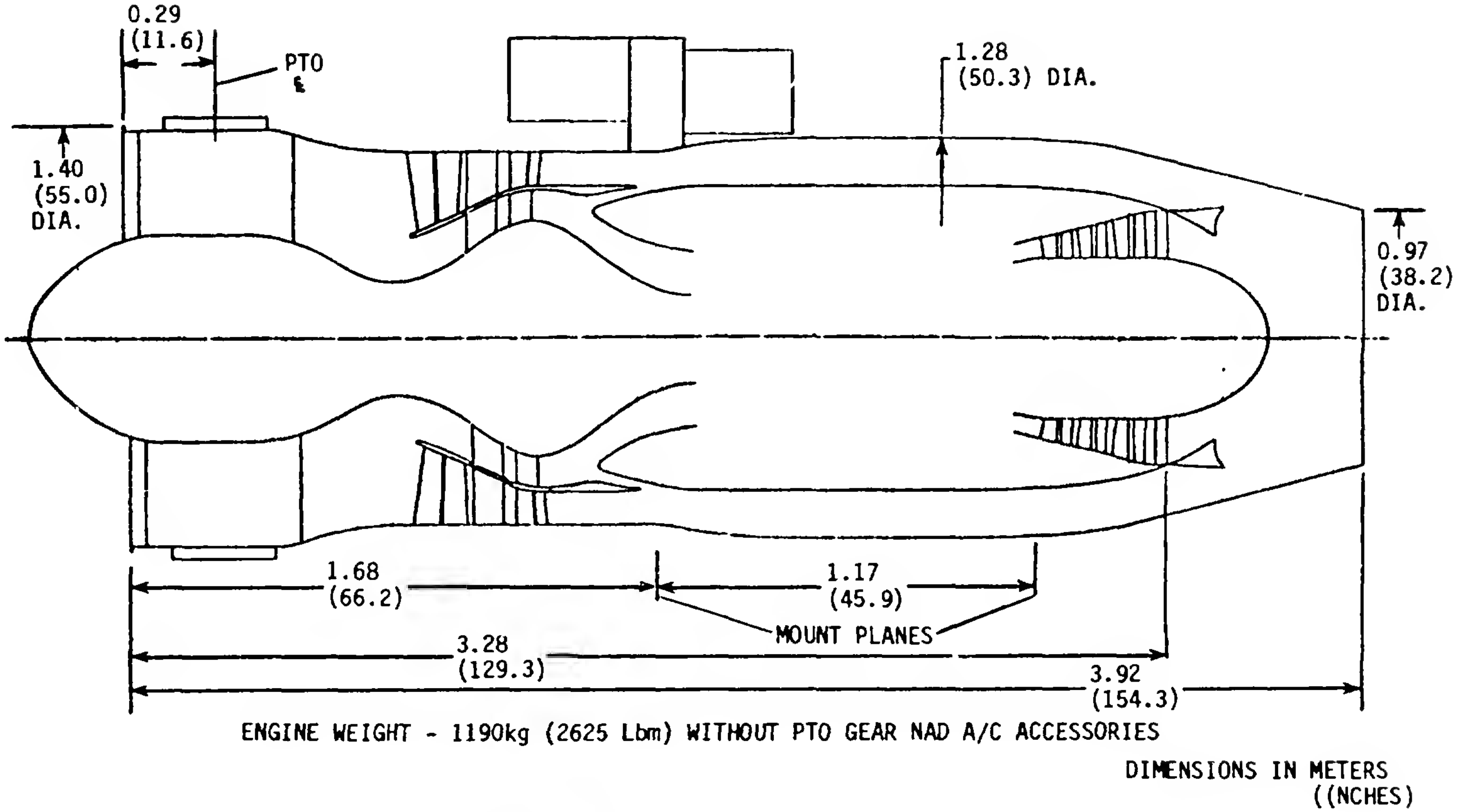


Figure 24. Task II X-Wing VIGV Convertible Baseline Engine - Mission Size.

TASK II - BASELINE CONVERTIBLE POWERPLANT SELECTION - Continued

BASELINE ROTORCRAFT/CONVERTIBLE VIGV ENGINE

The sizing criteria used for the ABC and X-Wing convertible engine aircraft are similar to their separate engine counterparts except maximum static sea level thrust is a fallout from sizing the engine for OEI, ISA + 15°C (27°F), 100% maximum power at T/W = 1.03.

Baseline ABC Rotorcraft - Convertible Engines

The baseline ABC rotorcraft with convertible engines is basically identical to the separate engine ABC except for elimination of the shaft turbines, their drive shafts and inlets, and replacement of the fan engines with convertible fan/shaft engines as seen in the three-view in Figure 25.

Shaft power to the rotor gearbox is transmitted by a right angle shaft from the engines with a dual input to the gearbox, similar to the separate engine configuration. Figure 26 illustrates the drive train configuration.

The ABC convertible VIGV engine configuration exhibits a 907 kg (2000 lb) reduction in gross weight compared to the separate engine baseline aircraft. As illustrated in Table 28, the aircraft sizing data are similar for the two configurations. The primary difference in gross weight is due to a reduction in engine weight. Table 29 compares the weight summary of the two aircraft. The VIGV configuration enables a simpler drive system arrangement, thus reducing weight.

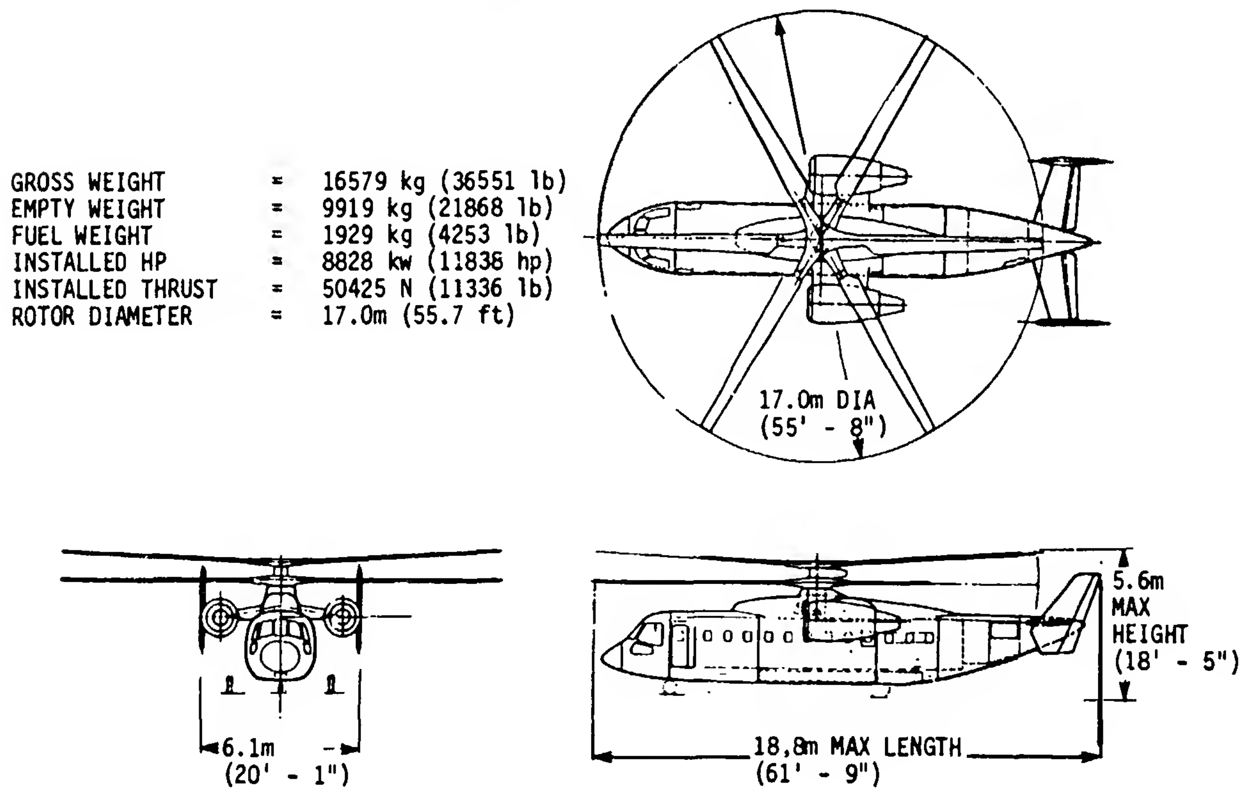


Figure 25. ABC Convertible Engine Aircraft.

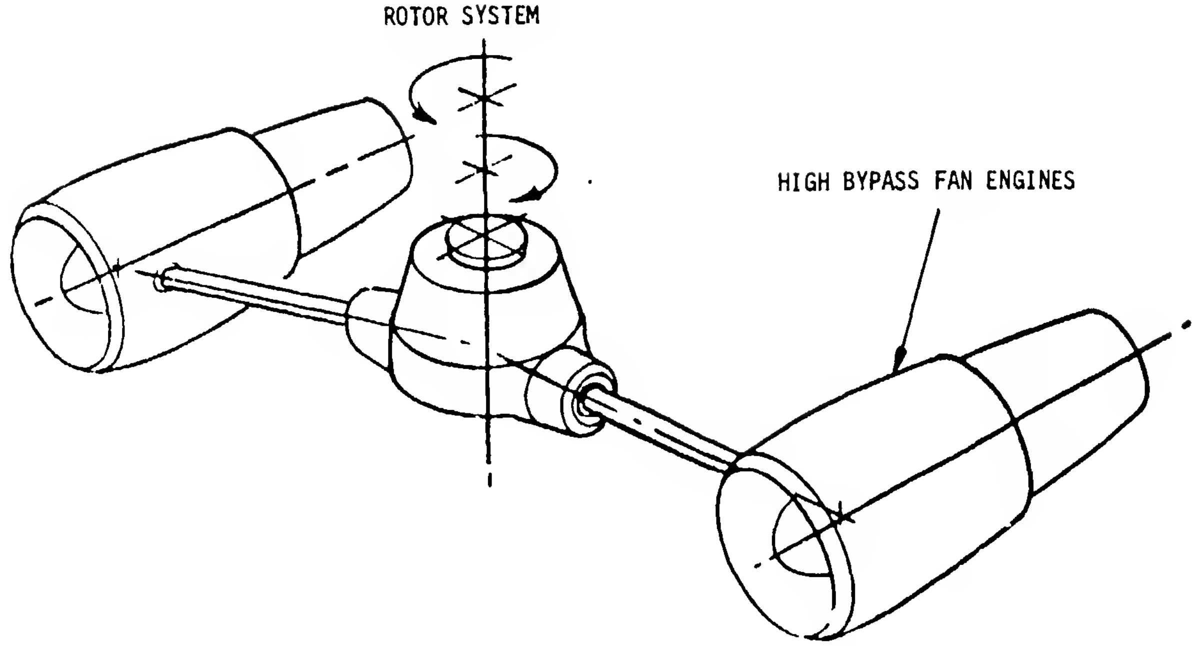


Figure 26. APC Convertible VIGV Drive System

The thrust-power split for the VIGV aircraft is obtained similarly to the separate engine aircraft. Based on the design criteria, the convertible engines are rated for the maximum static sea level conditions at 4414 kW (5919 hp) each and 25,212 N (5668 lb) thrust each. The reduction of installed shaft power is consistent with the reduction in gross weight. The installed thrust is increased over the separate engine aircraft due to a difference in engine lapse rates.

Fuel burn data for the design and off design missions are summarized in Table 30. Climb fuel increases since the VIGV aircraft has a lower climb rate than the separate engine aircraft. Comparatively, the fuel flows for the two aircraft are similar, with the lighter, VIGV aircraft showing a 5% reduction in total mission fuel. The difference in mission fuel translates as a 0.1% difference in direct operating cost. A breakdown of the VIGV aircraft direct operating cost is found in Figure 27. Two convertible engines are less costly to operate than four separate engines. Crew costs are slightly increased due to the longer mission time. Similarities between the airframe and dynamic systems of the two aircraft result in similar operating costs. The convertible VIGV configuration offers a 6.4% savings in DOC compared to the separate engine aircraft.

To facilitate engine cycle and configuration parametric studies, various rotorcraft sensitivities to propulsion system changes were generated. Rotorcraft sizing, performance and economics were determined for independent 5% increments in fuel flow, engine weight, and transmission weight. Additional sensitivities in direct operating costs were determined for independent 5% increments in engine maintenance and engine acquisition costs.

TABLE 28. TASK I & II ABC AIRCRAFT DESIGN COMPARISON	ABC Separate Engine Configuration	ABC Convertible Engine Configuration
Gross Weight, kg (lb)	17486 (38551)	16579 (36551)
Weight Empty, kg (lb)	10.731 (23659)	9919 (21868)
Fixed Useful Load, kg (lb)	376 (830)	376 (830)
Payload, kg (lb)	4354 (9600)	4354 (9600)
Fuel Weight, kg (lb)	2024 (4462)	1929 (4253)
Fuselage Length, m (ft)	18.6 (60.9)	18 (59)
Fuselage Width, m (ft)	2.7 (8.7)	3 (10)
Horizontal Tail:		
Aspect Ratio	5.05	5.05
Span, m (ft)	6.0 (19.6)	5.8 (19.1)
Thickness/Chord	0.12	0.12
Mean Chord, m (ft)	1.2 (3.9)	1.2 (3.8)
Vertical Tail:		
Aspect Ratio	1.5	1.5
Span, m (ft)	3.6 (11.7)	3.6 (11.7)
Thickness/Chord	0.15	0.15
Mean Chord, m (ft)	2.4 (7.8)	2.4 (7.8)
Main Rotor:		
Diameter, m (ft)	17.4 (57.2)	17.0 (55.7)
Solidity	0.1604	0.1604
Disc Loading, kg/m^2 (lb/ft^2)	73 (15)	73 ([illegible])
Tipspeed, m/s (ft/s)	204 (670)	204 ([illegible]0)
Aerodynamic:		
Total Effective Flatplate Drag, m^2 (ft)	2.3 (24.9)	2.3 (24.3)
Total Wetted Area, m^2 (ft^2)	167 (1794)	164 (1762)
Mean Skin Friction Coeff.	0.01388	0.01376
Aircraft Efficiency Factor	0.88071	0.88071

TABLE 29A. TASK I AND II ABC WEIGHT BREAKDOWN - KILOGRAMS

Engines	Separate	VIGV Fans
Body	1633	1602
Rotor	1450	1361
Tail Surfaces	55	52
Tail Rotor	-	
Landing Gear Group	655	631
Flight Controls	668	639
Fixed Equipment	2087	2087
Vibration Absorbers	175	166
Turboshafts or Prop/Shafts		
Engines	1085	-
Mounts and Pylons	23	-
Firewalls	12	-
Inlets, Cowling, and Exhaust	46	-
Controls	32	-
Starters	76	-
Turbofans or VIGV Fans		
Engines	738	1407
Mounts and Pylons	27	44
Firewalls	10	13
Inlets, Cowling and Exhaust	43	146
Controls	32	32
Starters	51	98
Fuel System	219	208
PTO Gear	111	159
Prop(s) and Installation	-	-
Prop Gear	-	-
Prop Transmission	-	-
Misc. Gears and Shafts	1503	1274
Weight Empty	10731	9919
Crew	327	327
Trapped Liquids and Oil	50	50
Payload	4354	4354
Fuel	2024	1929
Gross Weight	17486	16579

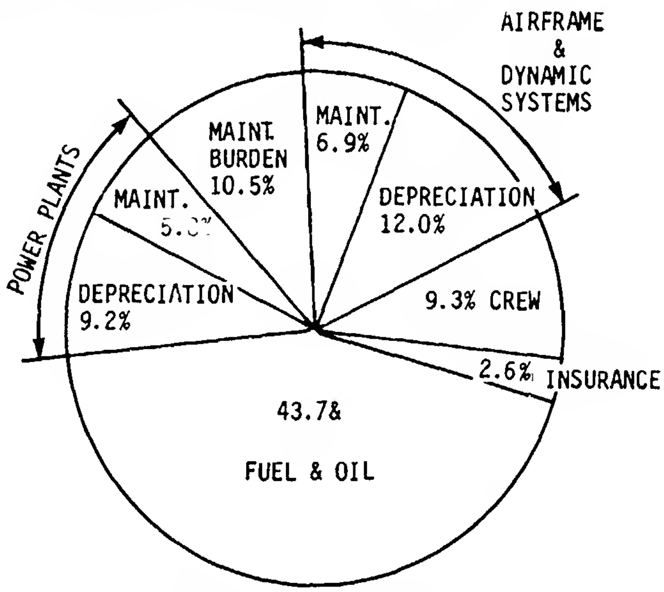
TABLE 29B. TASK I AND II ABC WEIGHT BREAKDOWN - POUNDS

Engines	Separate	VIGV Fans
Body	3600	3531
Rotor	3197	3000
Tail Surfaces	121	115
Tail Rotor		
Landing Gear Group	1445	1391
Flight Controls	1473	1409
Fixed Equipment	4600	4600
Vibration Absorbers	386	366
Turboshafts or Prop/Shafts		
Engines	2392	
Mounts and Pylons	52	
Firewalls	26	
Inlets, Cowling, and Exhaust	102	
Controls	70	
Starters	167	
Turbofans or VIGV Fans		
Engines	1627	3103
Mounts and Pylons	58	98
Firewalls	23	28
Inlets, Cowling and Exhaust	95	321
Controls	70	70
Starters	114	217
Fuel System	482	459
PTO Gear	244	350
Prop(s) and Instruction		
Prop Gear		
Prop Transmission		
Misc Gears and Shafts	3315	2810
Weight Empty	23659	21868
Crew	720	720
Trapped Liquids and Oil	110	110
Payload	9600	9600
Fuel	4462	4253
Gross Weight	38551	36551

TABLE 30. AIRCRAFT FUEL BURNED SUMMARY - TASK I AND II
ABC ROTORCRAFT

Powerplant	Fuel Burned, kg (lbm) Separate Engines		Convertible Engines	
Design Mission				
Takeoff	57	(125)	65	(145)
Climb	72	(160)	150	(330)
Cruise	1268	(2795)	1123	(2475)
Reserve	626	(1380)	592	(1305)
Total	2023	(4460)	1930	(4255)
Economic Mission				
Ground Handling and Takeoff	29	(65)	36	(80)
Climb	68	(150)	86	(190)
Cruise	1002	(2210)	896	(1975)
Air Maneuver	39	(85)	36	(80)
Descent and Approach	39	(85)	50	(110)
Block Fuel	1177	(2595)	1104	(2435)

370 km (200 min) MISSION, STD DAY, 65% LOAD FACTOR
$.528/1 ($2.00/GALLON) FUEL, 1981 DOLLARS



TOTAL DOC = 9.5¢/Seat = km
(17.7¢/ Seat - nmi)

Figure 27. ABC Convertible Engine DOC Summary

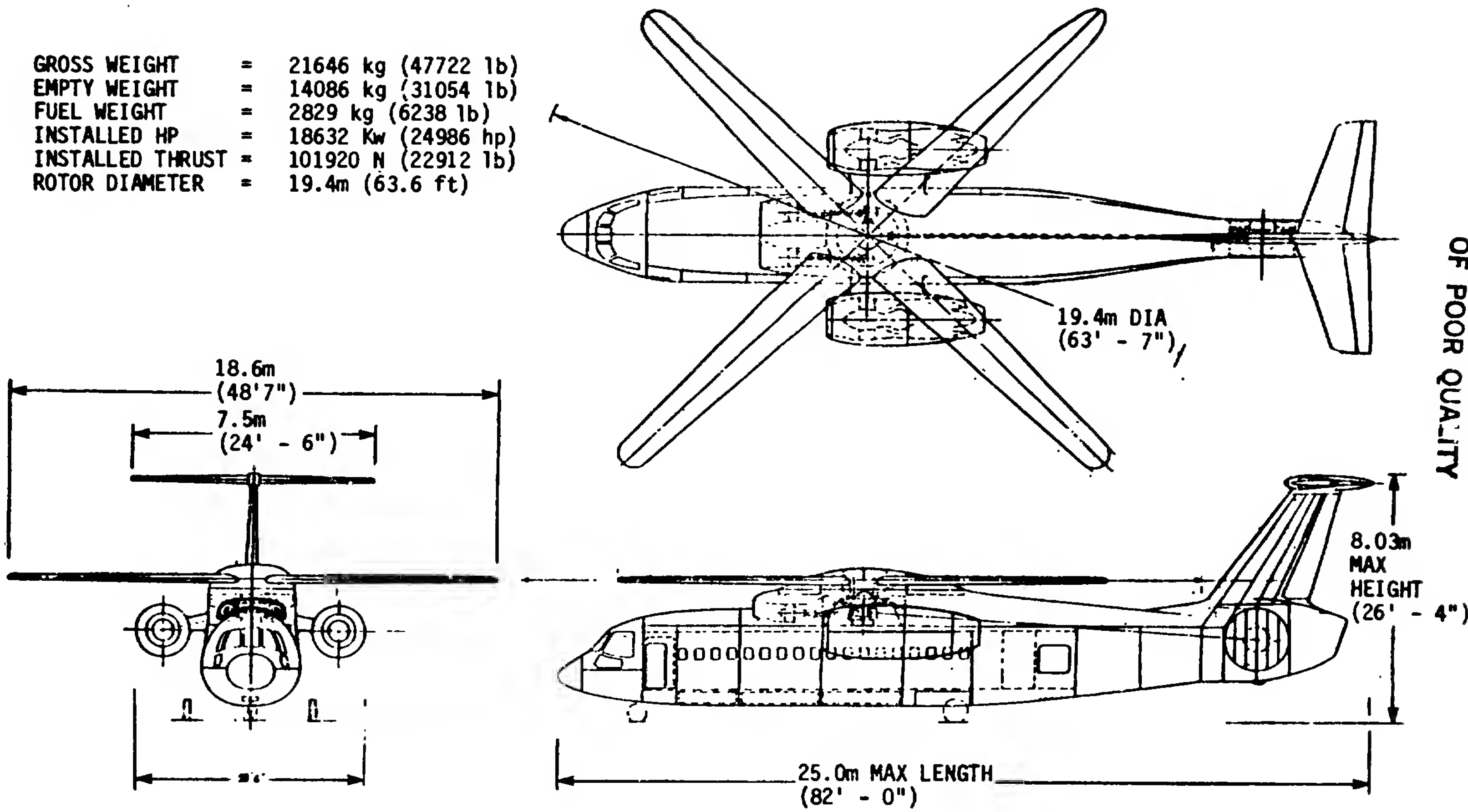


Figure 28. X-Wing Convertible Engine

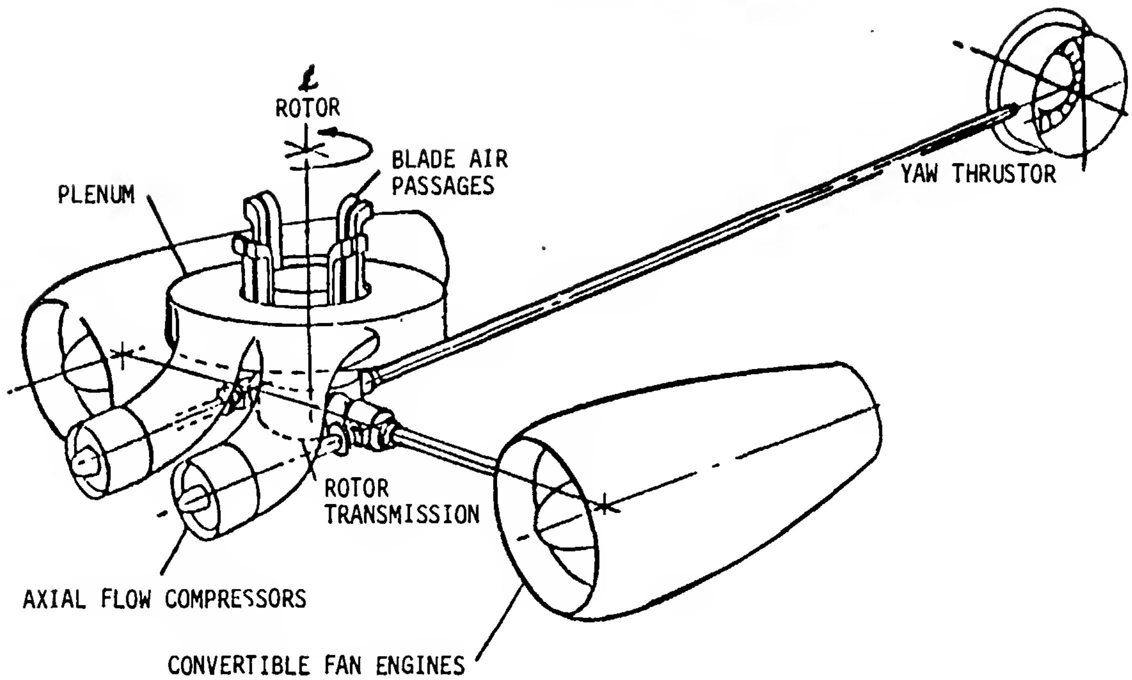


Figure 29. X-Wing Convertible VIGV Drive System

Since the payload requirements define the cabin size, the X-Wing convertible VIGV configuration is similar in size to the separate engine aircraft. The aircraft design summary is found in Table 31. Significant changes include a 2m (6 ft) reduction in cabin length and a 14.3% reduction in rotor/wing area. With its reduced size, the VIGV aircraft weighs 3598 kg (7931 lb) less than the separate engine aircraft. Employing only 2 VIGV engines considerably reduces weight. Significant weight savings are also due to a smaller drive system and rotor/wing area. Detailed aircraft weight breakdowns are compared in Table 32.

Propulsion is provided by convertible engines with a thrust-power split of 50,960N (11456 lb) thrust each and 9316 kW (12493 hp) each at maximum static sea level conditions. A reduction in gross weight requires less shaft power, as evident from comparing installed shaft power of the separate engine to the VIGV engine aircraft. Since the drag of the VIGV aircraft is reduced, a lower thrust required is apparent. However, the installed thrust increases due to the VIGV engine's higher lapse rate.

The VIGV configuration uses 7.5% less fuel than the separate engine aircraft. Table 33 illustrates the fuel breakdown for the separate engine and VIGV configurations. Cruise fuels are almost identical, however actual cruise distances varies. The VIGV aircraft cruises 6.9% farther, resulting from a higher climb rate and shorter climb distance, than the separate engine aircraft. The lower fuel flow rate of the VIGV's is noted by the reduced fuel burn during the reserve fuel segment.

Considerable savings in direct operating cost is attained with the VIGV aircraft as illustrated in Figure 30. Even though VIGV fuel constitutes a larger portion of the operating cost than separate engine fuel, the actual VIGV aircraft mission fuel costs less. The convertible engine airframe, dynamic systems and power plant maintenance and depreciation costs are significantly reduced due to the smaller airframe and engine size, and the reduction from 4 to 2 engines.

BASELINE ROTORCRAFT/CONVERTIBLE VIGV ENGINE - Continued

Baseline X-Wing Rotorcraft - Convertible Engines

As in the case of the ABC, the baseline X-Wing rotorcraft with convertible engines is very similar to the separate engine configuration except for replacement of the fan engines with convertible fan/shaft engines and the elimination of the shaft engines. As seen in the three-view in Figure 28, dual inputs to the main rotor/wing gearbox transmit the shaft power from the outboard mounted convertible engines. A schematic of the drive system is illustrated in Figure 29.

TABLE 31. AIRCRAFT DESIGN SUMMARY

	X-Wing Separate Engine Configuration	X-Wing Convertible Engine Configuration
Gross Weight, kg (lb)	25244 (55653)	21646 (47722)
Weight Empty, kg (lb)	17455 (38482)	14086 (31054)
Fixed Useful Load, kg (lb)	376 (830)	376 (830)
Payload, kg (lb)	4354 (9600)	4354 (9600)
Fuel Weight, kg (lb)	3058 (6741)	2830 (6238)
Fuselage Length, m (ft)	25 (82)	23 (76)
Fuselage Width, m (ft)	3 (10)	3 (10)
Horizontal Tail:		
Aspect Ratio	4.53	4.53
Span, m (ft)	7.9 (25.9)	7.0 (23.1)
Thickness/Chord	0.10	0.10
Mean Chord, m (ft)	1.7 (5.7)	1.6 (5.1)
Vertical Tail:		
Aspect Ratio	1.95	1.95
Span, m (ft)	4.6 (15.2)	4.1 (13.5)
Thickness/Chord	0.10	0.10
Mean Chord, m (ft)	2.3 (7.8)	2.1 (6.9)
Main Rotor/Wing:		
Area, m^2 (ft^2)	55.3 (594.8)	47.4 (510.0)
Diameter, m (ft)	20.9 (68.7)	19.4 (63.6)
Solidity	0.1604	0.1604
Disc Loading, kg/m^2 (lb/ft^2)	73 (15)	73 (15)
Tipspeed, m/s (ft/s)	198 (650)	198 (650)
Aerodynamic Data:		
Total Effective Flatplate Drag, m^2 (ft^2)	1.58 (16.96)	1.46 (15.76)
Total Wetted Area, m^2 (ft^2)	308 (3315)	293 (3152)
Mean Skin Friction Coeff.	0.00512	0.00517
Aircraft Efficiency Factor	0.8251	0.8[illegible]51

TABLE 32A. TASK I AND II X-WING WEIGHT BREAKDOWN - KILOGRAMS

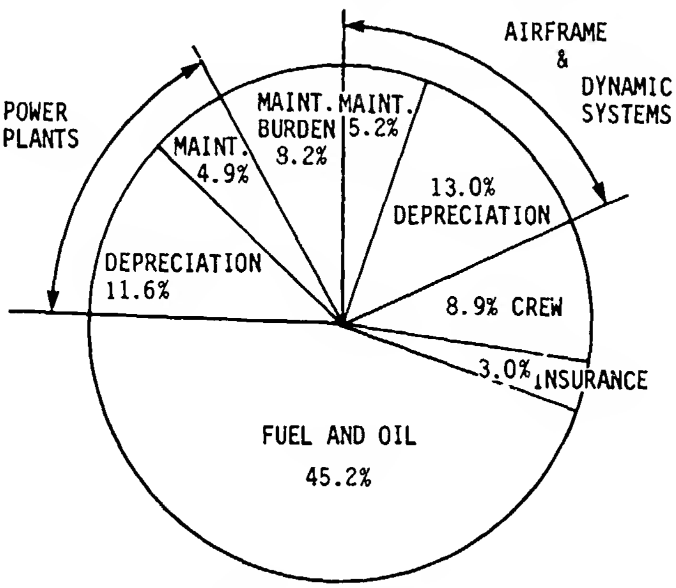
Engines	Separate	VIGV Fans
Body	2459	2397
Rotor	1842	1550
Tail Surfaces	447	357
Tail Rotor	47	47
Landing Gear Group	947	812
Flight Controls	1193	1033
Fixed Equipment	2214	2214
Vibration Absorbers	-	-
Turboshafts or Prop/Shafts		
Engines	2607	-
Mounts and Pylons	57	-
Firewalls	21	-
Inlets, Cowling, and Exhaust	108	-
Controls	32	-
Starters	182	-
Turbofans or VIGV Fans		
Engines	1760	2381
Mounts and Pylons	74	80
Firewalls	16	17
Inlets, Cowling and Exhaust	197	278
Controls	32	35
Starters	123	167
Fuel System	328	309
PTO Gear	218	294
Prop(s) and Installation	-	-
Prop Gear	-	-
Prop Transmission	-	-
Misc. Gears and Shafts	2306	1870
Compressors	245	245
Weight Empty	17455	14086
Crew	327	327
Trapped Liquids and Oil	50	50
Payload	4354	4354
Fuel	3058	2829
Gross Weight	25244	21646

TABLE 32B. TASK I AND II X-WING WEIGHT BREAKDOWN - POUNDS		
Engines	**Separate**	**VIGV Fans**
Body	5422	5285
Rotor	4062	3416
Tail Surfaces	985	786
Tail Rotor	103	103
Landing Gear Group	2087	1790
Flight Controls	2631	2278
Fixed Equipment	4880	4880
Vibration Absorbers	-	-
Turboshafts or Prop/Shafts		
Engines	5747	-
Mounts and Pylons	125	-
Firewalls	46	-
Inlets, Cowling, and Exhaust	237	-
Controls	70	-
Starters	402	-
Turbofans or VIGV Fans		
Engines	3880	5250
Mounts and Pylons	164	177
Firewalls	35	38
Inlets, Cowling and Exhaust	435	613
Controls	70	77
Starters	272	367
Fuel System	724	682
PTO Gear	481	649
Prop(s) and Installation	-	-
Prop Gear	-	-
Prop Transmission	-	-
Misc. Gears and Shafts	5084	4123
Compressors	540	540
Weight Empty	38482	31054
Crew	720	720
Trapped Liquids and Oil	110	110
Payload	9600	9600
Fuel	6741	6238
Gross Weight	55653	47722

TABLE 33. AIRCRAFT FUEL BURNED SUMMARY - TASK I AND II X-WING ROTORCRAFT

Powerplant	Fuel Burned, kg (lbm) Separate Engines		Convertible Engines	
Design Mission				
Takeoff	204	(450)	129	(285)
Climb	612	(1350)	522	(1150)
Cruise	1608	(3545)	1610	(3550)
Reserve	633	(1395)	569	(1255)
Total	3057	(6740)	2830	(6240)
Economic Mission				
Ground Handling and Takeoff	109	(240)	77	(170)
Climb	515	(1135)	488	(1075)
Cruise	1254	(2765)	1211	(2670)
Air Maneuver	54	(120)	54	(120)
Descent and Approach	274	(605)	259	(570)
Block Fuel	2206	(4865)	2089	(4605)

883km (450 nmi) MISSION, STD DAY, 85% LOAD FACTOR
$.594/1 ($2.25/GALLON) FUEL, 1981 DOLLARS



TOTAL DOC - 8.7¢/ Seat - km
(16.1¢/ Seat - nmi)

Figure 30. X-Wing Convertible Engine DOC Summary

COMPARISON OF TASK I AND TASK II ROTORCRAFT

Despite the compromises involved in designing one engine to perform the dual tasks of producing power and thrust, the fuel burn, weight, and economic savings associated with reducing the number of powerplants from 4 to 2 give the convertible engine powered rotorcraft a distinct advantage over the separate engine powered designs.

ABC Rotorcraft

Table 34 compares the mission size powerplants of the Task I and Task II ABC vehicles. (For the purposes of this table, a "powerplant" is one convertible engine, or the combination of one turboshaft and one turbofan). The convertible engine burns more fuel at takeoff, when it is in the turboshaft mode, because of the parasitic load of the fan tip windage.

At cruise, however, the overall cycle efficiency of the convertible engine is better than the separate engine combination, resulting in an 11% reduction in standard day, mid cruise fuel flow. Roughly half of this saving is due to the reduction in aircraft gross weight, the rest is due to the cycle efficiency improvement. A qualitative understanding of this improvement in cycle efficiency may be obtained by considering the following: cycle efficiency improves with increases in turbine temperature and/or cycle pressure ratio. The "average" values of T41 and pressure ratio for the separate engines may be obtained by weighting the individual values according to the useful output of each engine (power for the turboshaft, thrust x flight speed for the turbofan). When this is done for the ABC, the "average" T41 and pressure ratio for the separate engines are lower than for the convertible engine at cruise. Thus, the convertible engine is more efficient.

Engine weight, price, and maintenance expense are all on the order of 10 to 20% lower for the convertible powerplant than for the separate engines. The elimination of redundant components has a significant impact on weight (reduced 11%), and an even greater effect on maintenance (reduced 21%) through the elimination of an entire hot section. (The hot section - combustor and high pressure turbine - typically accounts for 40 to 50% of engine maintenance.) The engine price effect is smaller (reduced 11%) because of the cost adders associated with the VIGV design (see Variable Inlet Guide Vane Convertible Engine Section, pages 43 - 45).

Table 35 presents a comparison of the mission analysis results for the Task I and Task II ABC's. (See the Baseline ABC Rotorcraft - Separate Engines section, page 25 and the Baseline ABC Rotorcraft - Convertible Engines section, pages 44-50 for additional detail.) Table 36 compares the weight breakdowns of the two aircraft.

X-Wing Rotorcraft

The powerplant comparison in mission size is shown in Table 37 for the two X-Wing vehicles. Aircraft gross weight is 14% lower for the convertible engine powered version, but fuel consumption at takeoff is reduced only slightly (less than 2%) because of the penalty associated with fan tip power losses in the closed VIGV mode. At cruise, the fuel consumption rate with the convertible engines is 10 to 12% lower than with the separate powerplants. A decrease of the same order as the gross weight change (14%) might have been anticipated; however, the overall cycle efficiency at cruise of the convertible engines is somewhat worse than the separate engine combination. The weighted "sverage" values of T41 and cycle pressure ratio for the separate engines in this case are higher (implying better cycle efficiency) than for the convertible.

Table 38 gives a mission results comparison of the Task I and Task II X-Wing rotorcraft, and Table 39 gives the aircraft weight breakdowns.

TABLE 34A. COMPARISON OF CONVERTIBLE AND SEPARATE ENGINES
ABC ROTORCRAFT

SI Units

Mission Size, 1981 Economy

	Task I Separate Engines	Task II Convertible Engines
Aircraft Gross Weight, kg	17485	16580
ISA +15°C OEI Power, kW	4080	3890
Design Cruise, 3048 m, 463 km/h, ISA +10°C		
Output Power, kW	1530	5220
Thrust, N	8290	7985
Fuel Flow, kg/h		
ISA Normal Takeoff	620	745
ISA Mid Cruise	785	696
Powerplant Weight, kg	912	703
Powerplant Price, \$ X 10^{-3}	1730	1530
Powerplant Maintenance, \$/hr	68.00	54.00

TABLE 34B. COMPARISON OF CONVERTIBLE AND SEPARATE ENGINES
ABC ROTORCRAFT

English Units

Mission Size, 1981 Econcmy

	Task I Separate Engines	Task II Convertible Engines
Aircraft Gross Weight, lbm	38550	36550
ISA +27°F OEI Power, hp	5470	5210
Design Cruise, 10000 ft, 250 kt, ISA +18°F		
Output Power, hp	2050	1790
Thrust, lbf	1860	1795
Fuel Flow, lbm/hr		
ISA Normal Takeoff	1370	1650
ISA Mid Cruise	1730	1535
Powerplant Weight, lbm	2010	1550
Powerplant Price, \$ x 10^{-3}	1730	1530
Powerplant Maintenance, \$/hr	68.00	54.00

TABLE 35. MISSION ANALYSIS COMPARISON, TASK I AND TASK II, ABC ROTORCRAFT

Standard Day, 370 km (200 nmi) Mission

65% Load Factor, \$.528/l (\$2.00/gal) Fuel

1981 Economy

	Task I Separate Engines	Task II Convertible Engines	% Change
Aircraft Gross Weight, kg (lbm)	17485 (38550)	16580 (36550)	-5.2
Aircraft Acquisition Cost, \$ x 10^{-6}	8.522	7.991	-6.2
Block Fuel, kg (lbm)	1175 (2595)	1105 (2435)	-6.2
Direct Operating Cost, ¢/seat·km (¢/seat·nmi)	10.2 (18.9)	9.5 (17.7)	-6.5

TABLE 36. AIRCRAFT WEIGHT COMPARISON, TASK I AND TASK II ABC ROTORCRAFT

	Task I Separate Engines		Task II Convertible Engines	
	kg	(lbm)	kg	(lbm)
Turboshaft Engines	1085	(2390)	-	-
Turbofan Engines	740	(1630)	-	-
Convertible Engines	-	-	1410	(3105)
Installation	350	(775)	330	(735)
Drive System	1615	(3560)	1435	(3160)
Propulsion Sub Total	3790	(8355)	3175	(7000)
Airframe	2340	(5165)	2285	(5035)
Main Rotor	1450	(3200)	1360	(3000)
Equipment and Controls	3150	(6940)	3100	(6835)
Crew and Payload	4730	(10430)	4730	(10430)
Fuel	2025	(4460)	1930	(4250)
Gross Weight	17485	(38550)	16580	(36550)

TABLE 37A. COMPARISON OF CONVERTIBLE AND SEPARATE ENGINES X-WING ROTORCRAFT

SI Units

Mission Size, 1981 Economy

	Task I Separate Engines	Task II Convertible Engines
Aircraft Gross Weight, kg	25240	21650
ISA +15°C OEI Power, kW	9570	8050
Design Cruise, 9144 m, 741 km/h, ISA +10°C		
Output Power, kW	270	255
Thrust, N	12820	11480
Fuel Flow, kg/h		
ISA Normal Takeoff	1580	1550
ISA Mid Cruise	910	810
Powerplant Weight, kg	2184	1190
Powerplant Price, $ x 10^{-3}	2850	2220
Powerplant Maintenance, $/hr	86.00	66.70

TABLE 37B. COMPARISON OF CONVERTIBLE AND SEPARATE ENGINES X-WING ROTORCRAFT

English Units

Mission Size, 1981 Economy

	Task I Separate Engines	Task II Convertible Engines
Aircraft Gross Weight, lbm	55650	47720
ISA +27°F OEI Power, hp	12830	10800
Design Cruise, 30000 ft, 400 kt, ISA +18°F		
Output Power, hp	360	340
Thrust, lbf	2880	2580
Fuel Flow, lbm/hr		
ISA Normal Takeoff	3480	3420
ISA Mid Cruise	2000	1790
Powerplant Weight, lbm	4815	2625
Powerplant Price, $ x 10^{-3}	2850	2220
Powerplant Maintenance, $/hr	86.00	66.70

TABLE 38. MISSION ANALYSIS COMPARISON, TASK I AND TASK II X-WING ROTORCRAFT

Standard Day, km (450 nmi) Mission

85% Load Factor, $.594/l ($2.25/gal) Fuel

1981 Economy

	Task I Separate Engines	Task II Convertible Engines	% Change
Aircraft Gross Weight, kg (lbm)	25240 (55650)	21650 (47720)	-14.3
Aircraft Acquisition Cost, $ x 10^{-6}	13.0	11.2	-13.8
Block Fuel, kg (lbm)	2205 (4865)	2090 (4605)	-5.4
Direct Operating Cost, \$/seat·km (¢/seat·nmi)	10.1 (18.7)	8.7 (16.1)	-13.7

TABLE 39. AIRCRAFT WEIGHT COMPARISON, TASK I AND TASK II X-WING ROTORCRAFT

	Task I Separate Engines		Task II Convertible Engines	
	kg	(lbm)	kg	(lbm)
Turboshaft Engines	2610	(5750)	-	-
Turbofan Engines	1760	(3880)	-	-
Convertible Engines	-	-	2380	(5250)
Installation	840	(1855)	575	(1270)
Drive System	2525	(5565)	2170	(4775)
Propulsion Sub Total	7735	(17050)	5125	(11295)
Airframe	3900	(8595)	3615	(7965)
Main Rotor	1840	(4060)	1550	(3415)
Equipment and Controls	3980	(8775)	3800	(8375)
Crew and Payload	4730	(10430)	4730	(10430)
Fuel	3055	(6740)	2830	(6240)
Gross Weight	25240	(55650)	21650	(47720)

TASK III

ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES

ALTERNATIVE POWERPLANTS FOR ABC ROTORCRAFT

The VIGV turbofan was selected as the baseline convertible engine during Task II studies. The purpose of Task III was to consider alternate powerplant systems for comparison to the baseline. This Task was structured to include a screening of candidate propulsion systems proposed by NASA and General Electric on the basis of powerplant characteristics only. On the basis of the screening, the best alternate system was also evaluated in a rotorcraft mission relative to the baseline convertible VIGV turbofan shown on Figure 31.

The powerplant systems which were included in the screening for both the ABC and X-Wing rotorcraft are listed in Table 40. The discussion of alternate ABC systems will be divided into fan types and prop/shaft types. The choice between the studies involves the fundamental choice of a thrusting device between a fan and a propeller.

Alternate Fan Types - ABC

The two alternate fan types, a VP fan and a remote fan/parallel LPT are compared to the baseline VIGV fan in terms of basic operating functions at Normal T/O, T/O with OEI and at cruise in the summary Table 41.

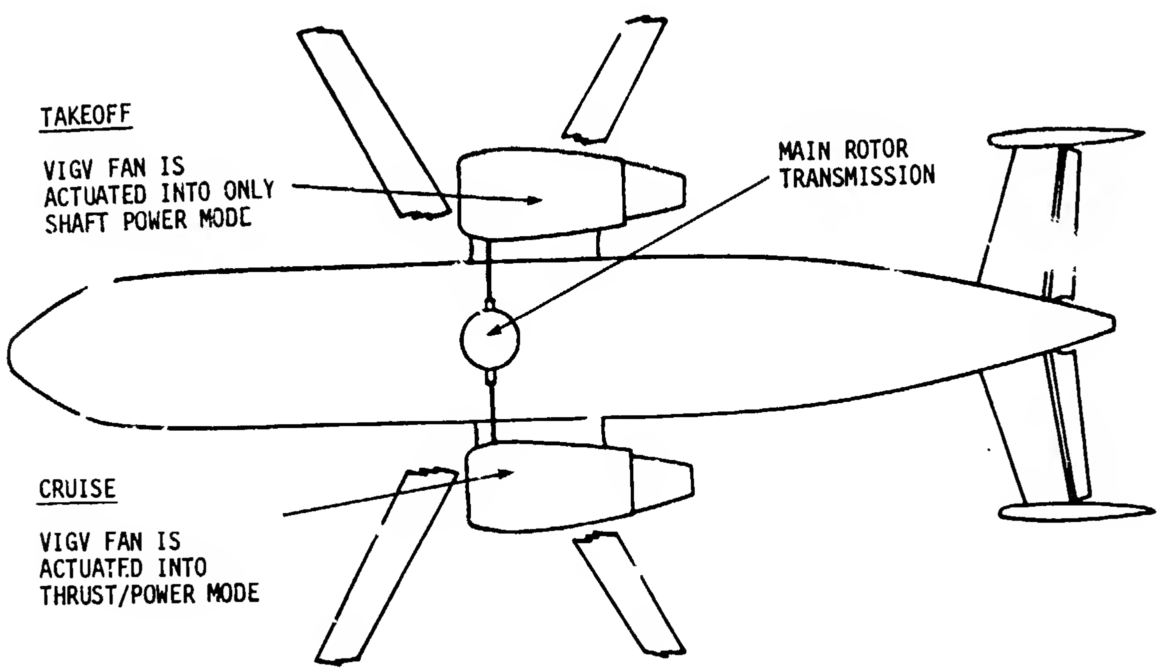


Figure 31. ABC Convertible VIGV

TABLE 40. TASK III - LIST OF SYSTEMS CONSIDERED DURING SCREENING EVALUATION

ABC Rotorcraft	X-Wing Rotorcraft
1. VIGV Fan - Base	1. VIGV Fan - Base
2. VP Fan	2. Remote Fan
3. Remote Fan/Parallel LPT	3. Prop/Shaft
4. Prop/Shaft	
5. Remote Parallel LPTS (Close to GG)	
6. Remote Parallel LPTS (Close to Prop)	
7. Remote Series LPTS	
8. Remote Parallel LPTS (Common to Both GGs)	

TABLE 41. ALTERNATIVE FAN TYPES - MODES OF OPERATION ABC ROTORCRAFT

	VIGV Fan	VP Fan	Remote Fan/Parallel LPT
Normal T/O	VIGV Closed for Minimum Thrust and Low Windage Losses	VP Closed for Minimum Thrust and Low Windage Losses	On-Off Valve Closed Fan Stops
T/O with OEI	VIGV Closed Shaft Power of One Engine Adequate (Sizes Core) Overriding Clutch Disconnect Idle Fan	VP Closed	On-Off Valve Closed Overriding Clutch Disconnects Idle Rotor LPT
Cruise	VIGV Partly Closed to Meet FN + Rotor rpm	VP Partly Closed to Meet FN and Rotor rpm	On-Off Valve Open 2 VATNS and Fan Speed Float to Match FN, SHP and Rotor rpm

TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

ALTERNATIVE POWERPLANTS AND ABC ROTORCRAFT - Continued

The VP fan engine achieves conversion from the fan mode to the shaft mode by closing fan blades rather than closing variable guide vanes as in the baseline convertible engine. This engine is installed pylon-mounted with a right angle power takeoff drive shaft supplying power to the main rotor gear box as shown on Figure 32. The VP fan was studied for the ABC rotorcraft because the low tip speed limitations of this design in turn restrict it to low fan pressure ratio application, more likely to pay off in the lower flight speed ABC mission. The VP fan has an inherent advantage of providing thrust modulation through zero into reverse thrust.

The remote fan/parallel turbines propulsion system is depicted on Figure 33. It consists of an unsupercharged gas generator driving two LPT's, both equipped with Variable Area Turbine Nozzles (VATN's). One single stage turbine drives the rotor, while the other LPT drives a remote fan, mounted off a fuselage pylon. At takeoff the gas flow is shut off to the fan LPT and all of the gas flow exhausts through the rotor LPT with the VATN wide open. As the fan

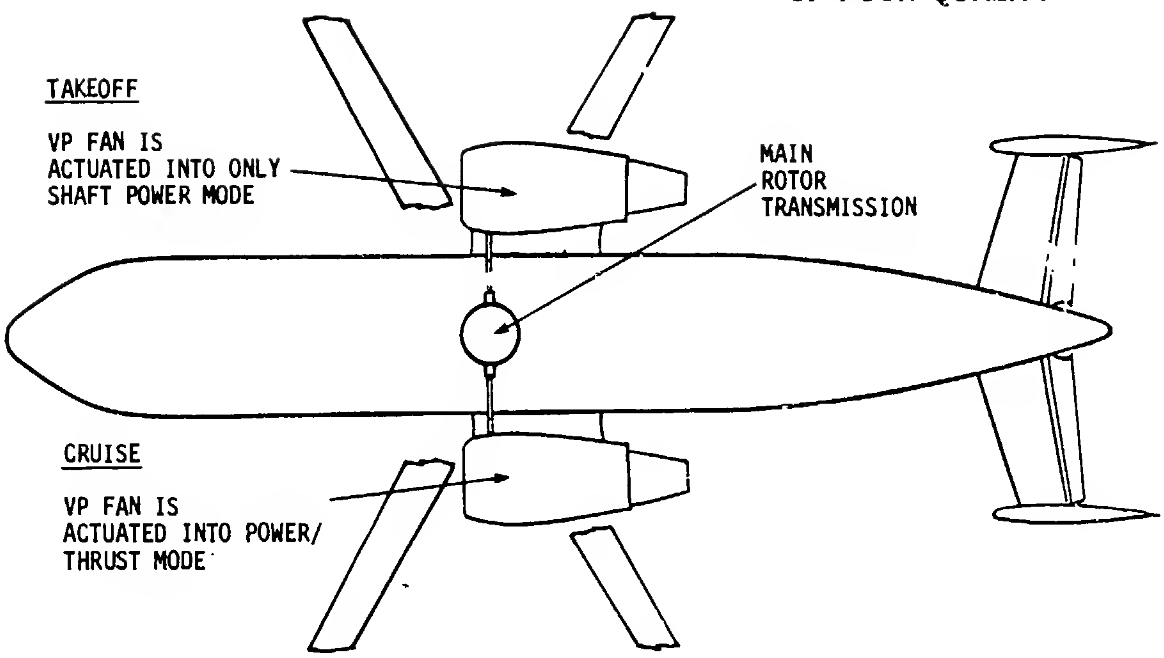


Figure 32. ABC Convertible - VP Fan

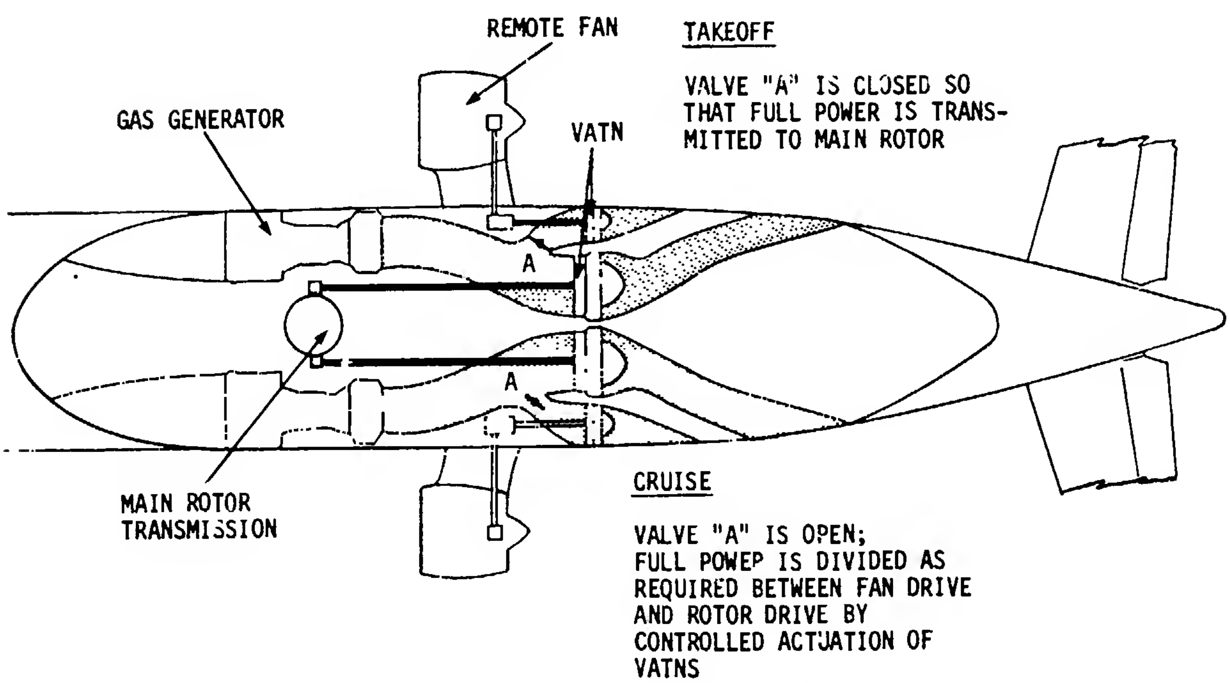


Figure 33. Remote Fan/Parallel Turbines - ABC Rotorcraft

ALTERNATIVE POWERPLANTS AND ABC ROTORCRAFT - Continued

VATN is opened to provide fan power, the rotor LPT VATN must be closed to compensate. The fixed geometry remote fan design pressure ratio was selected at 1.36, identical to the separate and VIGV fans to eliminate propulisve efficiency differences.

Alternate Shaft Types

The five alternate shaft types enumerated in Table 40 all drive a single pusher propeller mounted at the rear. This installation was chosen by Boeing Vertol as the best overall solution to ground clearance, noise, structural and aerodynamic factors. Figure 34 shows two "prop/shaft" turboshaft engines driving into the rotor gear box through a bevel gear transmission. The propeller is driven by a long extension shaft located over the top of the cabin. Safety dictates that the propeller be declutched on the ground, when the engine is idling and passengers are being loaded. In case of OEI, the inoperative engine is disconnected by an over running clutch between it and the rotor gear box. The modes of operation of these engines are outlined on Table 42.

Figures 35 and 36 show the rotorcraft in top elevation with remote parallel LPTs close to the gas generator and close to the propulsor. The propeller LPT can be unpowered at takeoff by closing the on-off valve and power sharing can be accomplished by modulating the two VATNs. The two types are very similar illustrating the weight and performance trades of shaft transmission vs. gas duct transmission. In the event of an engine (gas generator) failure, the LPTs associated with the active engine supply all the propeller and rotor power. The LPTs fed by the inoperative gas generator are declutched from the propeller and rotor by over running clutches.

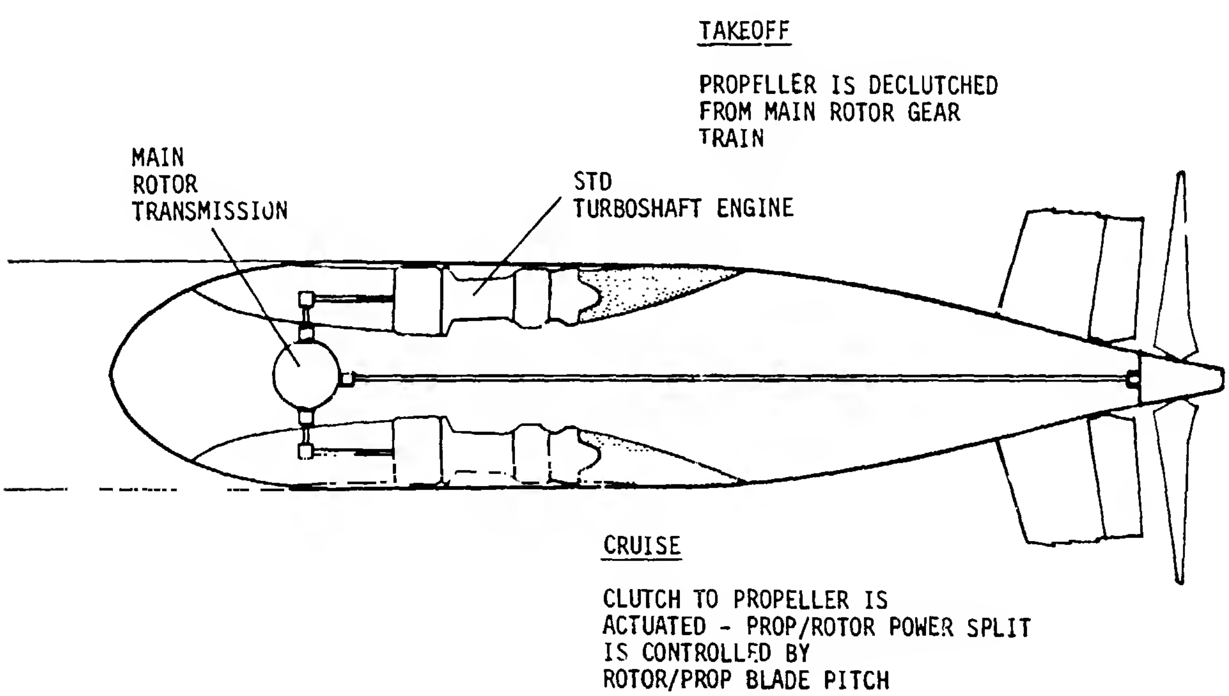


Figure 34. Prop/Shaft - ABC Rotorcraft

TABLE 42. ALTERNATE SHAFT TYPES - MODES OF OPERATION ABC ROTORCRAFT				
	Prop/Shaft Prop/Shaft	Remote Parallel LPT (Close to GG*) or (Close to Prop)	Remote Parallel LPT (Common to Both GG)	Remote Series LPT*
Normal Takeoff	Prop declutched for safety. Power to rotor.	On/Off valve closed. Power to rotor. Rotor LPT VATN* open.	Two prop On/Off valves closed. All power to rotor LPT, VATN open.	Diverter valve set to bypass prop LPT and produces residual FN.*
Takeoff With OEI	Over-running clutch disengages inoperative engine LPTs.		Rotor LPT On/Off valve closes to isolate inoperative GG. VATN open.	Overunning clutch disengages inoperative rotor LPT.
Cruise	Prop pitch setting sets prop power demand to match rotor rpm and rotor power demands.	On/Off valve open. VATNs set to match relative power demands of rotor and prop. Prop speed can be set independently by prop pitch.	All valves open. Prop and rotor VATN's fed from each GG are coordinated to match FN and SHP. Prop pitch can be set independently to prop schedules.	Diverter valve set to flow through prop LPT. VATN controls FN vs. SHP power demand. Prop pitch can be set independently to prop RPM schedule.

*GG = gas generator; LPT = low-pressure turbine; FN = net thrust; VATN = variable area turbine nozzle.

Figure 37 illustrates the remote series LPT propulsion system. Here all the gas flow passes through an LPT which requires no variable geometry. This turbine extracts the total power required to drive the overhead rotor. In the lift mode, the total flow from the rotor drive turbine is exhausted overboard, which means that the full gas pressure ratio will be available for this condition. In the forward flight mode, the diverter valve is opened and the total gas flow is directed through the propeller drive turbine assembly. However, now the full gas pressure ratio is split between the two-drive turbines as the VATN on the prop drive turbine operates to balance the rotor/prop power demands. In this system, the full available pressure ratio is split between the drive turbines with each operating at 100% gas flow as contrasted with the parallel systems, where the gas flow is split between the drive turbines with each operating at 100% available pressure ratio. The option of a common parallel remote LPT propulsion system is shown schematically on Figure 38. The LPT inlet scrolls are equally divided to isolate the exhaust gas supply from each of the two gas generators. On/off valves are required in each duct; for the rotor LPTs, in case of OEI to ensure system isolation, and for the propeller LPT to permit power shut-down during takeoff operations. The main advantage would be reducing the number of remote units from 4 to 2. However, the size of these units would increase substantially.

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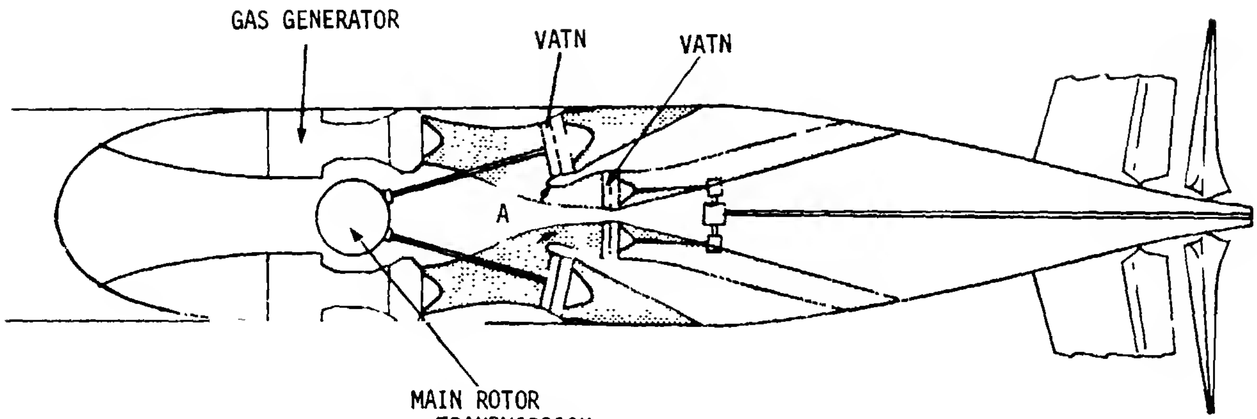

Figure 35. Remote Parallel LPTS - ABC Rotorcraft

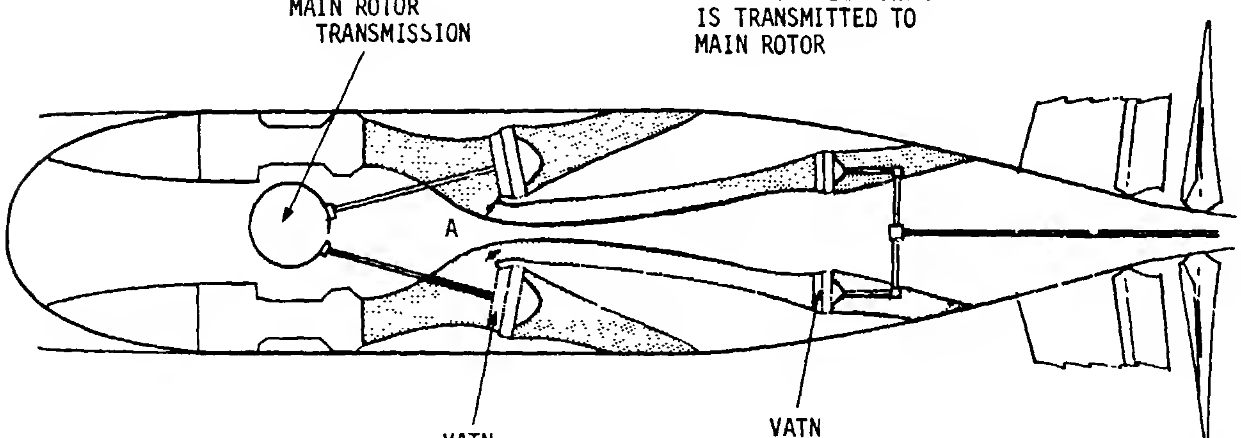

Figure 36. Remote Parallel LPTS - ABC Rotorcraft

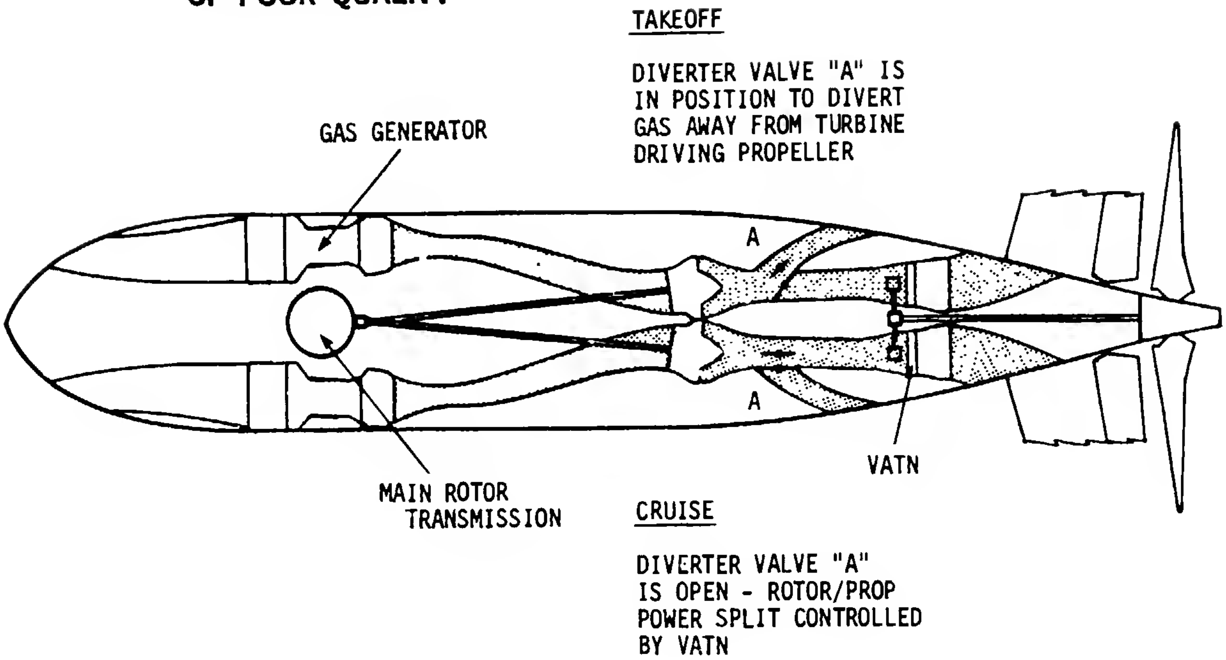

Figure 37. Remote Series LPTS - ABC Rotorcraft

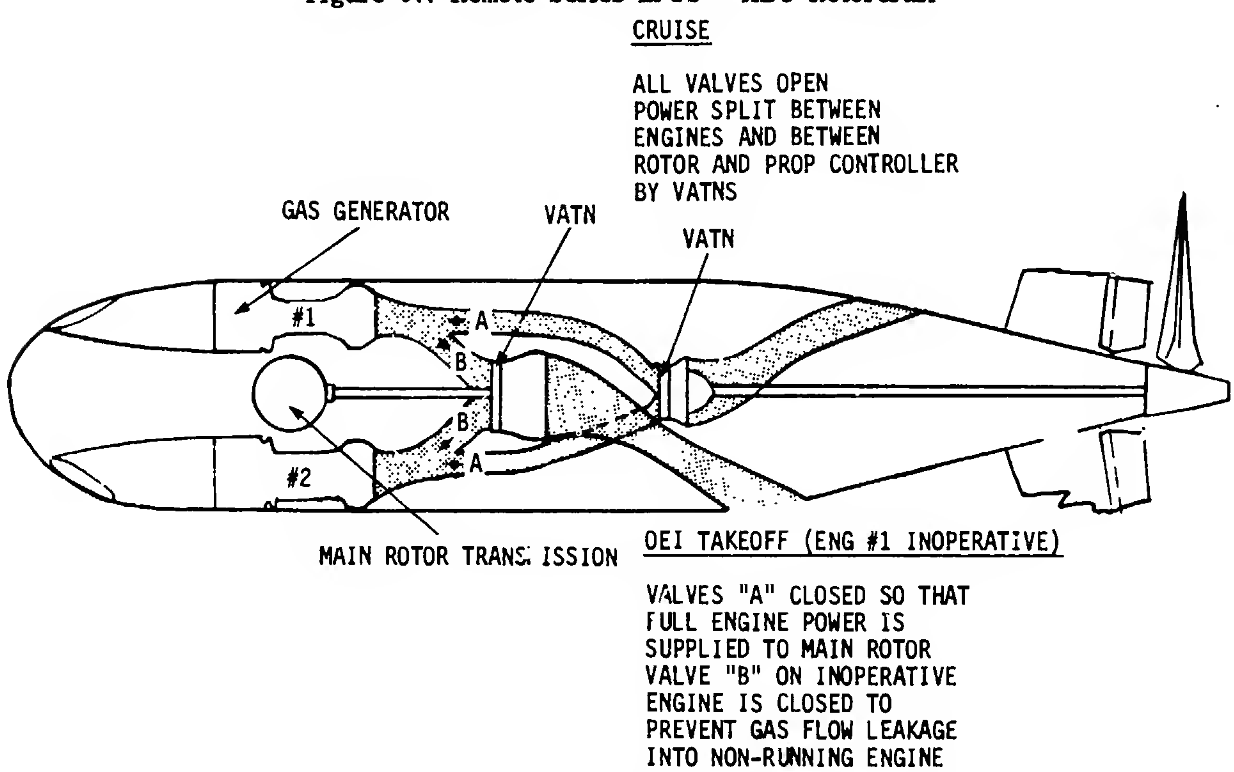

Figure 38. Remote Parallel LPTS - ABC Rotorcraft

ALTERNATIVE POWERPLANTS AND ABC ROTORCRAFT - Continued

Evaluation of ABC Alternative Powerplant

The major powerplant system characteristics which were determined for screening were weight and fuel consumption on a quantitative basis and other factors such as cost, maintenance, installability, complexity, reliability, safety operational factors and noise on a qualitative basis.

Performance and Weight

The fan types are grouped together in Table 43. The VP fan fuel flow rate is 1% higher than the VIGV fan. This is due to the lower fan efficiency of the VP fan and also due to the loss in cycle pressure ratio associated with the lower fan hub supercharge. There is also a weight increase of 3% due to the larger fan and core. The VP fan weight was estimated with composite material which is not considered an adequate design to survive a bird impact.

The fuel flow of the remote fan is 14% higher than the baseline. This is mainly due to 3% for VATN efficiency panalties, 2% for inlet protection, and 7.0% for ducting pressure losses.

The system weight is up by 23%, of which 1.5% is due to duct and diverter valve weights, 3.5% for larger core engine and 18% for the aggregate weight of the two VATN LPTs and a remote fan vs. the single fan/LPT low speed shaft of the baseline engine.

The requirements for a VATN and inlet protection impose a certain design approach and it would be difficult to make a significant improvement within these boundaries. However, some benefit from reduced transmission system weights could be realized by incorporating the fan drive LPT directly into the fan/nacelle assembly to make a standard turbofan without its gas generator. This arrangement would also result in a lower system weight due to the elimination of the fan drive LPT as a separate structure.

The shaft types are grouped for performance and weight comparison in Table 44. The remote parallel LPTs are 7% higher in fuel flow than the baseline prop/shaft engine. This is due to 1.6% for hot gas transmission duct pressure losses and 2.9% due to the extra bleed flow required to pressurize a second LPT unit and 2.5% due to a LPT efficiency reduction. This LPT effect is the result of the prop turbine power (44% of the total power) being generated with 4.6% less efficiency due to VATN and 1.2% less due to map migration. i.e., 0.44 (-5.8%) = -2.5%. The system weight increases of 22-23% are due to the same factors and split approximately 3.0% for a larger core, 3.5% for the ducting and valves and 17% for the remote LPTs vs. the single LPT of the main engine assembly.

The remote series LPTs fuel consumption is comparable to the prop/shaft. This is due to the compensating effects of a 1.1% increase due to duct losses but an improvement of 1.0% in the combined LPT performance at cruise. In this case, the rotor LPT has no VATN and is a lower pressure ratio design and the prop VATN is fully open at cruise; also operating at a lower pressure ratio stage.

The system weight is also larger by 21% with 4% due to ducting and 17% due to remote LPT units, vs one centralized LPT. Although the series system approach has significantly improved the fuel consumption, it is still penalized by the fundamental weight adder due to the use of two LPT drive units. Because of the series split of the available p/p, the prop drive LPT is in fact larger than that of the parallel system. This partially reduces the weight savings from the smaller gas generator engine associated with the series system.

The common LPT in parallel fuel consumption increase is higher than the two remote LPT systems because the complicated valve/ducting losses are higher and because the efficiency of the common rotor drive LPT at its OEI sizing point is penalized by a partial arc decrement. In the

TABLE 43A. TASK III - ALTERNATE PROPULSION SYSTEMS PRELIMINARY ENGINE PERFORMANCE DATA - DESIGN SIZE - ABC ROTORCRAFT

SI Units

	VIGV Fan	VP Fan	2 Remote LPTs in Parallel Driving Rotor/Fan
$Alt/V_1/\Delta T_{amb}$	3 km/129 m/s/+10°C		
Condition	Initial Cruise/(Aero Design)		
Fn_{quote}, N	8349		
Output $Power_{quote}$, kW	1531		
Wf_{quote}, kg/h	800 (Base)	807 (+1%)	918 (+14%)
Fan Dia, m	.98	1.04	.92
Engine Inlet $W\sqrt{\theta}/\delta$, kg/s	89.5 (92) Aero-Design	(117.9)	(90.6)
Cycle P/P	22.6	22.2	21.9
Core $W\sqrt{\theta}/\delta$, kg/s	13.6 (15.4)	14.6 (17.4)	17.5 (17.6)
Core P/P	17.3 (22.0)	18.3 (22.0)	21.9 (22.0)
Fan P/P	1.34 (1.37)	(1.25)	(1.37)
$Alt/V_1/\Delta T_{amb}$	0/0/+15°C		
Condition	OEI Takeoff		
Output $Power_{quote}$, kW	4094*	4094*	4094
Core $W\sqrt{\theta}/\delta$, kg/s	14.0	17.4	17.5
Core P/P	17.9	22.0	22.0
ΔTotal Propulsion System Wt.-%	Base	$\boxed{+3}$	$\boxed{+23}$

*Net after windage

TABLE 43B. TASK III - ALTERNATIVE PROPULSION SYSTEMS PRELIMINARY ENGINE PERFORMANCE DATA - DESIGN SIZE - ABC ROTORCRAFT			
	English Units		
	VIGV Fan	VP Fan	2 Remote LPTs in Parallel Driving Rotor/Fan
$Alt/V_1/\Delta T_{amb}$	10K/250 kt/+18°F		
Condition	Initial Cruise/(Aero Design)		
Fn_{quote}, lbf	1877		
Output $Power_{quote}$, hp	2053		
Wf_{quote}, lbm/hr	1766 (Base)	1780 (+1%)	2023 (+14%)
Fan Dia, ft	3.2	3.4	3.0
Engine Inlet $W\sqrt{\theta}/\delta$, lbm/sec	197.3 (202.8) Aero-Design	(260)	(199.8)
Cycle P/P	22.6	22.2	21.9
Core $W\sqrt{\theta}/\delta$, lbm/sec	30.1 (34.0)	32.3 (38.4)	38.6 (38.8)
Core P/P	17.3 (22.0)	18.3 (22.0)	21.9 (22.0)
Fan P/P	1.34 (1.37)	(1.25)	(1.37)
$Alt/V_1/T_{amb}$	0/0/+27°F		
Condition	OEI Takeoff		
Output $Power_{quote}$, hp	5490*	5490*	5490
Core $W\sqrt{\theta}/\delta$, lbm/sec	30.8	38.4	38.8
Core P/P	17.9	22.0	22.0
Δ Total Propulsion System Wt-%	Base	$\boxed{+3}$	$\boxed{+23}$

*Net after windage

TABLE 44A. TASK III - ALTERNATIVE PROPULSION SYSTEMS PRELIMINARY ENGINE PERFORMANCE DATA - DESIGN SIZE - ABC ROTORCRAFT

SI Units

	Prop Shaft	2 Remote LPTs in Parallel Driving Rotor/Prop LPTs Close to GG	2 Remote LPTs in Parallel Driving Rotor/Prop LPTs Close to Propulsor	2 Remote LPTs in Series Driving Rotor/Prop	Common LPTs in Parallel Driving Rotor/Prop
$Alt/V_1/\Delta T_{amb}$	3 km/129 m/s/+10°C				
Condition	Initial Cruise				
Fn_{quote}, N	8349				
Output $Power_{quote}$, kW	1531				
Wf_{quote}, kg/h (Δ%)	687 (Base)	735 (+7)	735 (+7)	687	761 (+10)
Prop Dia., m	3.96				
Engine Inlet $W\sqrt{\theta}/\delta$, kg/s	-	-	-	-	-
Cycle P/P	19.5	20.5	20.5	19.8	20.2
Core $W\sqrt{\theta}/\delta$, kg/s	(15.5) 14.2	15.6 (17.1)	15.6 (17.1)	13.5 (15.4)	16.6 (18.5)
Core P/P	(22.0) 19.5 Aero-Design	20.5 (22.0)	20.5 (22.0)	19.8 (22.0)	20.2 (22.0)
$Alt/V_1/\Delta T_{amb}$	0/0/+15°C				
Condition	OEI Takeoff				
Output $Power_{quote}$, kW	4094	4094	4094	4094	4094
Core $W\sqrt{\theta}/\delta$, kg/s	15.5	17.1	17.1	15.4	18.5
Core P/P	22.0	22.0	22.0	22.0	22.0
Δ Total Propulsion System Wt-%	Base	$\boxed{+23}$	$\boxed{+22}$	$\boxed{+21}$	$\boxed{+17}$

TABLE 44B. TASK III - ALTERNATIVE PROPULSION SYSTEMS PRELIMINARY ENGINE PERFORMANCE DATA - DESIGN SIZE - ABC ROTORCRAFT

English Units

	Prop Shaft	2 Remote LPTs in Parallel Driving Rotor/Prop LPTs Close to GG	2 Remote LPTs in Parallel Driving Rotor/Prop LPTs Close to Propulsor	2 Remote LPTs in Series Driving Rotor/Prop	Common LPTs in Parallel Driving Rotor/Prop
$Alt/V_1/\Delta T_{amb}$	10K/250 Kt/+18°F				
Condition	Initia. Cruise				
Fn_{quote}, lbf	.877				
Output $Power_{quote}$, hp	2053				
Wf_{quote}, lbm/hr (Δ%)	1516 (Base)	1620 (+7)	1620 (+7)	1514	1677 (+10)
Prop Dia., ft	13.0				
Engine Inlet $W\sqrt{\theta}/\delta$, lbm/sec	-	-	-	-	-
Cycle P/P	19.5	20.5	20.5	19.0	20.2
Core $W\sqrt{\theta}/\delta$, lbm/sec	(34.1) 31.2	34.4 (37.8)	34.4 (37.8)	29.8 (33.9)	36.7 (40.7)
Core P/P	(22.0) 19.5 Aero-Design	20.5 (22.0)	20.5 (22.0)	19.8 (22.0)	20.2 (22.0)
$Alt/V_1/\Delta T_{amb}$	0/0/+27°F				
Condition	OEI Takeoff				
Output $Power_{quote}$, hp	5490	5490	5490	5490	5490
Core $W\sqrt{\theta}/\delta$, lbm/sec	34.1	37.8	37.8	33.9	40.7
Core P/P	22.0	22.0	22.0	22.0	22.0
ΔTotal Propulsion System Wt-%	Base	+23	+22	+21	+17

ALTERNATIVE POWERPLANTS AND ABC ROTORCRAFT - Continued

OEI mode, full gas flow from one engine must pass through only 50% of the total passage areas, with the other 50% arc causing substantial losses from arc end turbulence and pumping of spill-over flow from the active arc.

Of the 10% full consumption increase, 5% is due to duct losses and 5% due to the LPT/VATN penalties. These effects are closely associated with the OEI requirement and the use of commonality to decrease the number of separate units. Therefore, it is doubtful that research would provide any significant improvements with these system objectives in place.

The system weight for this arrangement is 17% higher than the baseline system. Of this total, 4% is due to a larger core, 4% is due to ducting and diverter valves and 9% is due to the larger remote LPT units associated with this system.

Powerplant System Complexity, Reliability and Safety

Among the other factors which were considered in a qualitative fashion in the comparison were the system complexity, reliability and safety.

Table 45 lists all the elements or subassemblies necessary for each system. The larger the number, the greater system complexity and inevitably the lower the overall reliability. Comparing the fan options first, the VIGV fan, the VP fan and the remote fan. The VP and VIGV fans are equivalent in complexity, although there are two fewer gear sets, actually a bevel gear set performing the same function is included in the VP engine. The remote fan requires additional elements such as diverter valves, VATNs, ducts and shafts resulting in higher complexity and lower reliability.

The fan systems are roughly equivalent from a safety standpoint. The VP fan is considered unsafe to bird impact. The remote fan with remote turbines close to the fuselage does have a safety disadvantage since there is always a finite danger of a disc failure.

A comparison of the prop/shaft and the other remote turbine systems shows that the prop/shaft has the fewest elements for lowest complexity and highest reliability.

Alternate System Noise

The alternate systems are compared in summary fashion in Table 46 with respect to community noise and cabin noise factors. The community noise assessment assumes that the rotor is no longer the dominant factor in an advanced high speed rotorcraft and that the propulsion system noise will be a concern.

The VIGV may have a community noise problem at takeoff with the VIGV fully closed. Also during descent, keeping the fan speed high will increase noise over a conventional turbofan. Cabin noise will be low, as expected for a turbofan. The VP fan may also have a noise problem at takeoff when the VP fan blade is closed. The remote fan presents no problems for community noise, but hot gas ducts will require acoustic insulation to shield the passenger compartment.

For the prop systems, the propeller itself will dominate over the engine and other propulsion system elements. The remote LPT/VATNs generate high frequencies which are hardly audible. The common remote LPT, however, generates frequencies lower than 10 KHz which will contribute some to community noise. Cabin noise presents a common problem for all prop systems. In addition the alternates present several other unique noise sources which must be reckoned with. The hot gas ducting near the passenger compartment must be acoustically insulated. Also there may be beat frequencies generated between the parallel LPTs operating at speeds without much separation

TABLE 45. PROPULSION SYSTEM COUNT - ABC ROTORCRAFT

	Alternate Propulsion Systems								
	Sep. Engines ABC	VIGV ABC	VP ABC	Prop Shaft ABC	Remote Fan ABC	Ind. Pt ABC	Ind/Remote ABC	LPT in Series ABC	Common LPTs in Parallel ABC
Conv. Engine		2	2						
Gas Generator					2	2	2	2	2
TF Engine	2								
TS Engine	2			2					
Inlet, Cowling and Exhaust	4*	2*	2	2*	2	2	2	2	2
Shaft Elements	2*	2*	2	5*	4	5	5	7	2
Gear Sets Excl. Main Rotor GB	2*	2		3*	2	1	1	1	
Clutch - Rotor									
Clutch - Propulsor				1					
Aux. Compressor(2)									
Ducting					6	6	6	6	6
Propeller Assy.(1) GB				1*		1*	1*	1*	1*
Fan Pod Assy.					2				
Overrunning Clutch		2	2	2		4	4	4	
Brake									1
Diverter/On-Off Valve					2	2	2	2	4
Power Turbine Assy.					4	4	4	4	2

*Weight and cost to be supplied by BV
(1) Includes gear, lube and prop. control systems
(2) Includes drive and shaft

TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

ALTERNATIVE POWERPLANTS AND ABC ROTORCRAFT - Continued

Operational Factors

Table 47 summarizes five other factors which were considered in the evaluation. Reverse thrust capability for takeoff or landing maneuvers is available with a propeller. The VP fan has limited reverse thrust capability. The VIGV fan has none. This characteristic is considered to be more important for military applications. The level of residual thrust is high for the VIGV and remote fans due to high core exhaust momentum. The VP fan can be reversed slightly to balance any core engine thrust. The propeller systems can all be modulated to zero thrust.

Bird strike capability is good for all systems except for the VP composite fan. Core FOD protection is provided by a supercharging fan stage, VIGV or VP which acts to centrifuge particles into the fan duct, whereas the isolated gas generator cases are more susceptible to damage.

TABLE 46. TASK III ALTERNATE POWERPLANTS FOR ABC ROTORCRAFT NOISE FACTORS		
	Community Noise*	Cabin Noise
VIGV	High speed fan will lead to high noise levels during descent. Closed IGV noise will be problem at Takeoff.	Low - like turbofan.
VP	Low frequency, blade-closed noise may be problem.	Low - like turbofan.
Remote Fan/ Parallel Turbines	Straight TF	Good like turbofan, except for duct insulation and Δ frequencies between LPT.
Prop/Shaft	Prop dominates.	Low frequency, difficult to attenuate.
Prop/Shaft Parallel LPT Close To GG	Prop dominates, remove LPT/ VATN high frequency - no concern.	Low frequency, difficult to attenuate. Δ frequencies between LPT's causes heat. Gas ducts must be insulated from cabin - weight penalty.
Prop/Shaft Parallel LPT Close To Prop	Prop dominates, remote LPT/ VATN high frequency - no concern.	Same as above except for longer ducts.
Prop/Shaft Series LPT	Prop dominates, remote LPT/ VATN high frequency - no concern.	Same as above. Duct length and location A factor.
Prop/Shaft Common Remote LPT	Prop dominates. Also turbine problem because of frequencies lower than 10 KHz.	Low frequency problem ducts must be insulated.

*Exclusive of rotor noise

TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

ALTERNATIVE POWERPLANTS AND ABC ROTORCRAFT - Continued

Summary Evaluation - ABC Alternate

Selection factor in addition to weight and SFC are listed in Table 48 with pluses and minuses assigned to each alternate system, on the basis of some quantitative estimate, but mostly on the basis of subjective judgment. The pluses and minuses should be read as "worse than" or "better than" the baseline system in that category. The distribution between one and two pluses or minuses is subjective. The basis for the subjective evaluation and the assignment of "grades" is summed up in Table 49.

The VIGV fan ranks second to the prop/shaft. The VP fan is really ruled out from safety considerations and none of the more complex remote prop systems are as good as the basic prop/ shaft system.

As a result of this evaluation, the prop/shaft was recommended for mission analysis in Task III versus the VIGV turbofan.

TABLE 47. OPERATIONAL FACTORS - ABC

	VIGV Fans	VP Fans	Remote Fans Parallel LPT	Prop Shaft	Remote Parallel LPT Prop	Remote Parallel Common LPT Prop	Remote Series LPT Prop
Level of Reverse FN Takeoff or Landing Maneuvers	None	Fair	None	Good	Good	Good	Good
Level of Residual FN at Takeoff in Hover	Poor	Good	Poor	Good	Good	Good	Good
Continuity of Thrust Variation and Range	Fair	Good	Fair	Good	Poor	Poor	Poor
Bird Strike Capability	Good	Unacceptable	Good	Good	Good	Good	Good
Core FOD Capability	Good	Good	Fair	Fair	Fair	Fair	Fair

TABLE 48. ROCOCO TASK III EVALUATION - ABC ROTORCRAFT SCREENING RATING SHEET

			Alternate Configurations						
Criteria	VIGV Fan	VP Fan	Remote Fan	Prop/ Shaft	Remote Parallel LPT's (Close to GG)	Remote Parallel LPT's (Close to Prop)	Remote Series LPT	Remote Parallel LPT's (Common to both GGs)
				With Propeller				
Powerplant Mission Weighted SFC - Δ% at Cruise	Base	+1	+14	-14	-8	-8	-14	-3
Powerplant Weight - Δ% Wt		+3	+23	+2	+25	+25	+24	+20
Powerplant Relative Cost		-	-	+	-	--	-	--
Powerplant Relative Maintenance Cost		-	--	+	-	--	-	--
Installability			-	-	-	--	-	--
Powerplant Complexity		-	--	-	--	--	--	-
System Reliability Assessment		-	--	-	--	--	--	-
System Safety Assessment		-	-	-				-
System External Noise		+	++	+	+	+	+	
System Cabin Noise			-	-	-	-	-	--
Ranking	2	3	5	1	4	8	6	7

Criteria Rating Code

+ Better than base engine
- Poorer than base engine
Blank - Same as base engine

TABLE 49. ROCOCO TASK III EVALUATION - ABC ROTORCRAFT ALTERNATE SYSTEMS

(Basis for Qualitative Evaluation in Table 48 Relative to VIGV Baseline)

Criteria	VIGV Fan	VP Fan	Remote Fan	Prop/ Shaft	Remote Parallel LPT's (Close to GG/Prop)	Remote Series LPT	Remote Parallel LPT's (Common to both GGs)
		Alternate Configurations					
				With Propeller			
Powerplant Relative Cost	Base	Higher Engine Cost	Add'l Cost of Remote Elements.	Lower Engine Cost Smaller. Lower System Cost.	Add'l cost of Remote Elements in System.		
Powerplant Relative Maintenance Cost		Higher First Cost	Higher Maint Cost on Separated Powerplants.	Lower System First Cost.	Higher maintenance cost of separated powerplants		
Installability		Similar to VIGV Baseline Fan	Ducts and Shafts.	Shafts and Gear-boxes.	Ducts and Shafts	Ducts and Shafts	Add'l Large Diameter Ducting
Powerplant Complexity		Based on Propulsion System Element Count Table 45.					
System Reliability Assessment		Based on Propulsion System Element Count Table 45.					
System Safety Assessment		Bird Strike Vulnerability	Core FOD Vulnerability.				No redundancy on Rotor Pt.
System External Noise				See Table 46 →			
System Cabin Noise				See Table 46 →			

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TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

ALTERNATIVE POWERPLANTS FOR X-WING ROTORCRAFT

The remote full span fan shown in Figure 39 was considered because it simplifies the fan aero design vs. a part span VIGV with high hub supercharge requirements presently under consideration as our baseline engine and shown on Figure 40. The fan is contained in a shaft-driven podded assembly, pylon mounted from the fuselage. The core LP output shaft drives the fan, bleed compressor and main rotor gear. The modes of operation are summarized in Table 50 for the two alternate systems to the VIGV fan. The remote fan mode of operation at normal T/O, OEI and cruise are identical to the VIGV fan.

The prop/shaft was also considered as an alternate, as depicted in Figure 41. Boeing Vertol chose the twin prop/shaft, high tail mounted installation for low cabin noise and to avoid interference with the X-Wing rotor. The turboshaft engine power train is forward to the bleed compressor and the main rotor gear box. The prop is driven by a single extension shaft driving into a combining gearbox over the top of the fuselage. The modes of operation are also outlined in Table 50. No clutch is required for the high tail mounted props which can rotate safely during passenger loading operations. During OEI operation, the inoperative engine LPT is disconnected by an over-running clutch and the compressors are driven from the rotor gear box. During cruise, the prop pitch setting will respond to hold the speed which will be set by a schedule as required by the bleed compressors and the power demanded of the props.

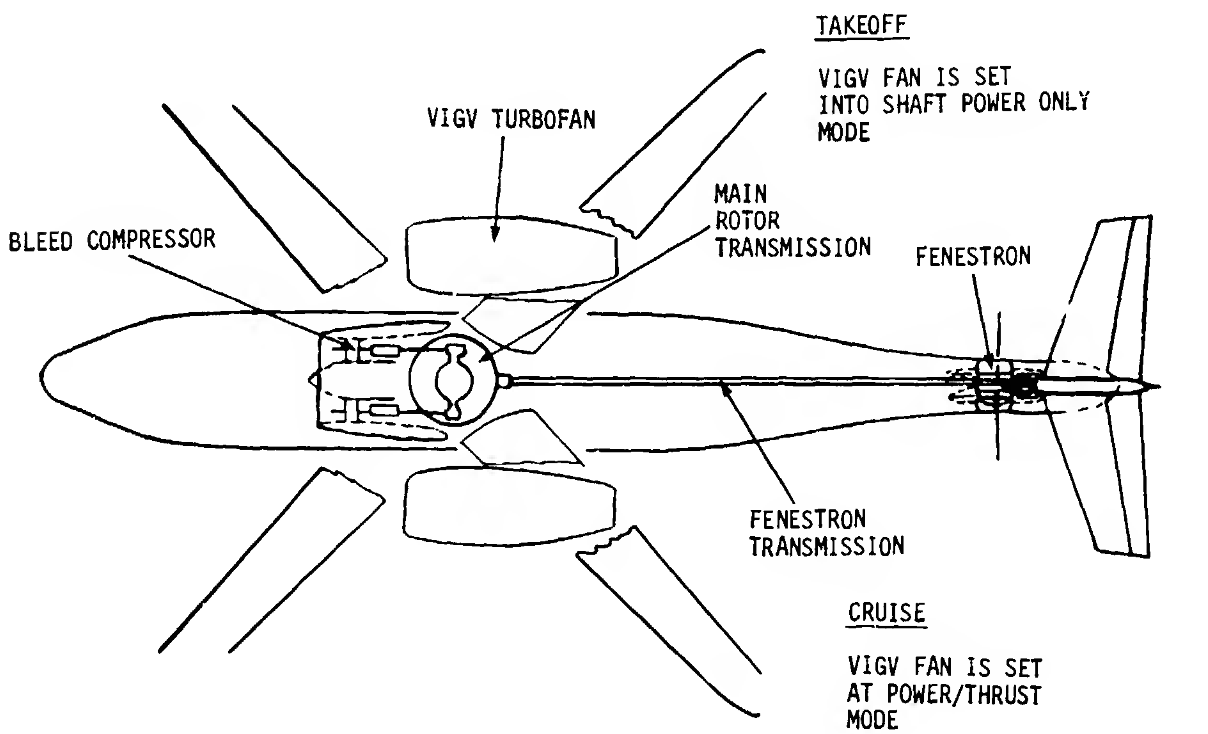

Figure 39. X-Wing Rotorcraft - Remote Fan

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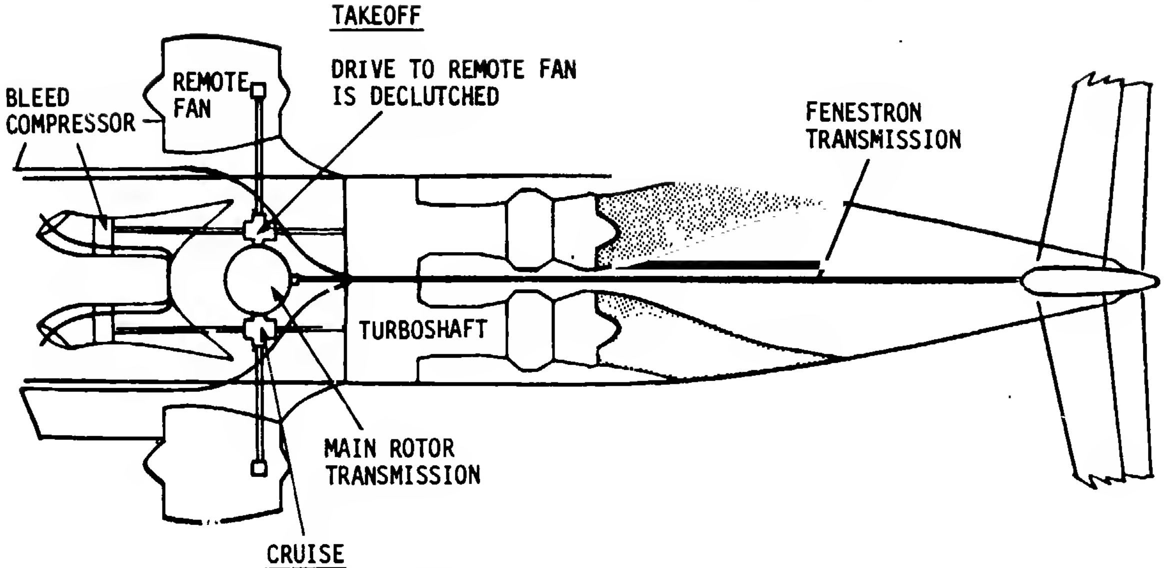

Figure 40. X-Wing Convertible VIGV

TABLE 50. X-WING ROTORCRAFT ALTERNATIVE PROPULSION SYSTEMS - MODES OF OPERATION

	VIGV/Fan	Remote Fan	Prop/Shaft
Normal Takeoff	VIGV Closed. Minimum Thrust. Windage Losses.	VIGV (Full Span) Closed. Minimum Thrust. Windage Losses.	Prop in flat pitch. For takeoff (min. windage). No clutch required. High location on tail.
Takeoff with OEI	VIGV Closed. → Shaft power of one engine adequate. (Sizing condition of core) Overrunning clutch disconnects idle fan.	→	Overrunning clutch disengages inoperative engine LPT. Compressors driven from rotor gearbox.
Cruise	VIGV partly closed → to meet FN, SHP* and rotor RPM (T41 and $\Delta\alpha$).	→	Prop pitch setting sets prop power demand to match rotor RPM and rotor power.

*SHP to rotor and bleed compressors.

Note: Conversion determines only bleed compressor size.

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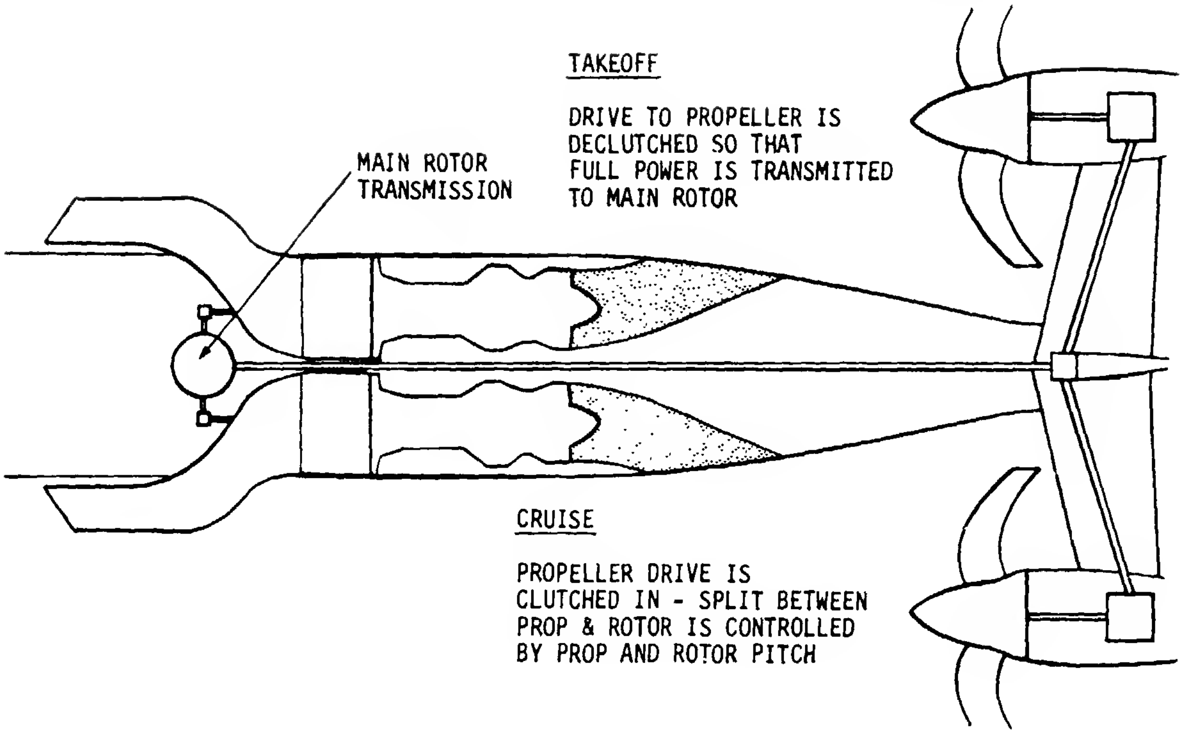

Figure 41. X-Wing Rotorcraft - Prop Shaft

X-Wing Alternate Powerplant Evaluation

The quantitative evaluation results, for SFC and weight, including the entire power train, are summarized in Table 51. For the prop/shaft engine, the cruise fuel flow rate is 20% lower than the VIGV fan baseline due to the high propulsive efficiency of a 82.7% prop/fan propeller. This is despite the lower cycle pressure ratio due to an unsupercharged core engine. However, the system weight is 14% greater which is due to a 1% larger core engine, 16% due to extra shafting and prop gear sets and the balance the net weight difference (-3%) of the props vs. an engine-integrated VIGV fan configuration.

The remote fan fuel rate at cruise is 3% greater than the baseline VIGV. This is mostly due to the lower effective cycle pressure ratio of the unsupercharged core and the gear losses involved in transmitting power to a remote fan. The weight increase is 19% of which 3% is traceable to a larger unsupercharged core and 5% is due to extra shafts and gear boxes and 11% due to the remote fan units vs. the LP systems of the VIGV turbofans.

Alternate X-Wing Powerplant Complexity, Reliability and Safety

The propulsion system elements are summarized in Table 52 for the two alternates in the VIGV baseline. The prop/shaft requires more shafts, gear boxes and bearings and is therefore likely to have a lower system reliability. The remote fan is close in complexity/reliability to the VIGV fan. It does have some extra shafting and gears compared to the VIGV system.

Both alternate systems received a somewhat lower safety rating because of the core engine proximity to the passenger compartment, compared to a pylon supported VIGV turbofan.

TABLE 51A. ALTERNATE PROPULSION SYSTEMS - TASK III PRELIMINARY ENGINE PERFORMANCE DATA - DESIGN SIZE - X-WING ROTORCRAFT

	VIGV Fan	Prop/Shaft Turboshaft Driving Rotor and Prop Fan	Remote Fan Turboshaft Driving Rotor and VIGV Fan
$Alt/V_1/\Delta T_{amb}$	9.1 km/206 m/s/+10°C →		
Condition	Initial Cruise/Aero Design →		
Fn_{quote}, N	12553 →		
Output $Power_{quote}$, kW	268 →		
Wf_{quote}, kg/h (Δ%)	932 (Base)	749 (-20)	959 (+3)
Fan Dia/Prop Dia, m	1.46/	/3.26	1.34/
Engine Inlet $W\sqrt{\theta}/\delta$, kg/s	181 (189.6) Aero-Design	-	211 (217.7)
Core $W\sqrt{\theta}/\delta$, kg/s	30.8 (36.1)	32 (36.4)	38.5 (40.2)
Cycle P/P	23.3	18.4	20.5
Core P/P	16.3 (22)	18.6 (22)	20.8 (22)
Fan P/P	1.56 (1.65)	-	1.54
$Alt/V_1/\Delta T_{amb}$	0/0/+15°C →		
Condition	OEI Takeoff →		
Output $Power_{quote}$, kW	9566*	9566	9566
Core $W\sqrt{\theta}/\delta$, kg/s	34.9	36.4	40.2
Core P/P	18.9	22.0	22.0
ΔTotal Propulsion System Wt.-%	Base	$\boxed{+14}$	$\boxed{+19}$

*Net after windage

TABLE 51B. ALTERNATE PROPULSION SYSTEMS - TASK III PRELIMINARY ENGINE PERFORMANCE DATA - DESIGN SIZE - X-WING ROTORCRAFT

English Units

	VIGV Fan	Prop/Shaft Turboshaft Driving Rotor and Prop Fan	Remove Fan Turboshaft Driving Rotor and VIGV Fan
Alt/V_1/ΔT_{amb}	30K/400 Kt/+18°F →		
Condition	Initial Cruise/Aero Design →		
Fn_{quote}, lbf	2822 →		
Output $Power_{quote}$, hp	360 →		
Wf_{quote}, lbm/hr (Δ%)	2055 (Base)	1651 (-20)	2114 (+3)
Fan Dia/Prop Dia, ft	4.8/	/10.7	4.4/
Engine Inlet $W\sqrt{\theta}/\delta$, lbm/sec	400.0 (418) Aero-Design	-	465 (480)
Core $W\sqrt{\theta}/\delta$, lbm/sec	68 (79.5)	70.6 (80.2)	84.9 (88.7)
Cycle P/P	23.3	18.4	20.5
Core P/P	16.3 (22)	18.6 (22)	20.8 (22)
Fan P/P	1.56 (1.65)	-	1.54
Alt/V_1/ T_{amb}	0/0/+27°F		
Condition	OEI Takeoff		
Output $Power_{quote}$, hp	12828*	12828	12828
Core $W\sqrt{\theta}/\delta$, lbm/sec	76.9	80.2	88.7
Core P/P	18.9	22.0	22.0
ΔTotal Propulsion System Wt.-%	Base	+14	+19

*Net after windage

TABLE 52. PROPULSION SYSTEM COUNT - X-WING ROTORCRAFT				
			Alternate Propulsion Systems	
	Separate Enginea X-W	VIGV X-W	Prop Shaft X-W	Remote Fan X-W
Conv. Engine		2		
Gas Generator				
TF Engine	2 req'd			
TS Engine	2		2	2
Inlet, Cowling and Exhaust	4*	2*	2*	2
Shaft Elements	2*	5*	7*	6
Gear Sets {Excl. Main Rotor GB}	2*	3	4*	4
Clutch - Rotor	1*	1*	1	1
Clutch - Propulsor				
Aux. Compressor(2)	2*	2*	2*	2*
Ducting	3*	3*	2*	
Propeller Assy.(1)			2*	
Fan Pod Assy.				2
Overrunning Clutch	2	2	2	2
Brake				
Diverter/On-Off Valve				
Power Turbine Assy.				

(1) Includes gear and system
(2) Includes drive and shaft

TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

ALTERNATIVE POWERPLANTS FOR X-WING ROTORCRAFT - Continued

Alternate X-Wing Powerplant Noise

Some of the qualitative factors are summarized in Table 53. As far as community noise is concerned, only the closed VIGV may present a problem on takeoff or approach. The full span VIGV remote fan will be somewhat noisier in this respect. For the prop/shaft the propeller will dominate.

The turbofans would present no cabin noise problem, and the prop location would ensure a cabin noise level requiring little attenuation.

X-Wing Alternate Powerplants - Operational Factors

The remote fan has the same characteristics as the VIGV fan, as summarized in Table 54 with the exception of core FOD capability. The turbofan core is better protected from ingested FOD, which the fan tends to centrifuge outward into the fan duct.

The prop/shaft engine has the advantage of reverse thrust and low thrust modulation. It also has the disadvantage of a relatively unprotected core. The X-Wing core is large, however, and not as vulnerable as the ABC core.

TABLE 53. TASK III ALTERNATE POWERPLANTS FOR X-WING ROTORCRAFT NOISE FACTORS		
	Community Noise*	Cabin Noise
VIGV	VIGV high speed fan, high noise during approach.	Low - like turbofan.
Prop/Shaft	Prop noise dominates.	Low frequency difficult to attenuate. Prop location minimizes penalty. Twin-beat frequency.
Remote Fan	Full span VIGV fan noise level higher than partial VIGV.	Low - like turbofan.

*Not including rotor.

TABLE 54. OPERATIONAL FACTORS - X-WING

	VIGV Fans	Remote Fan Shaft Driven VIGV	Prop/Shaft
Level of Reverse FN Takeoff or Landing Maneuvers	None	None	Good
Level of Residual FN at Takeoff in Hover	Poor	Poor	Good
Continuity of Thrust Variation and Range	Fair	Fair	Good
Bird Strike Capability	Good	Good	Good
Core FOD Capability	Good	Fair	Fair

TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

ALTERNATIVE POWERPLANTS FOR X-WING ROTORCRAFT - Continued

X-Wing Alternate Powerplants - Summary Evaluation

A summary of the major qualitative factors on Table 55 shows some factors to be considered but none of them are important enough to eliminate it.

The choice has to be made primarily on the basis of SFC and weight. The final screening rating Table 56 shows no clear advantage for the remote fan to justify its considerations. The prop/shaft was recommended for mission analysis to determine the net effect of the SFC reduction and weight increase relative to the baseline VIGV turbofan.

TABLE 55. CONVERTIBLE POWERPLANT SELECTION FACTORS (OTHER THAN DOC) X-WING ROTORCRAFT

	Advantages	Disadvantages
VIGV Fans	• Low system complexity.	• High speed fan noise at approach. • Hover thrust/maneuverability. Residual thrust/no reverse. • Limited data/experience on closed IGV operation. • Bleed compressor speed matching compromises performance.
Remote Fan/Shaft Driven	• More flexibility in fan design.	• Core FOD vulnerability greater. • More system complexity.
Prop/Shaft	• Moderate complexity. • No special engine development required. • Thrust modulation and reversal.	• Prop noise (community) may be problem. • Installation factors.

TABLE 56. ROCOCO TASK II EVALUATION - X-WING ROTORCRAFT SCREENING RATING SHEET

		Alternates	
Criteria	VIGV Fan	Remote Fan	Prop/Shaft
Powerplant Mission Weighted SFC % at Cruise	Base	+3	-20
Powerplant Weight % Wt		+19	+14
Powerplant Relative Cost		-	+
Powerplant Relative Maintenance Cost		-	+
Installability		-	-
Powerplant Complexity		-	-
System Reliability Assessment		--	-
System Safety Assessment		-	-
System External Noise		-	+
System Cabin Noise			-
RANKING	1	3	2

Criteria Rating Code

+ Better than base engine
- Poorer than base engine
Blank - Same as base engine

ROTORCRAFT WITH PROP/SHAFT ENGINES

The sizing criteria used for the ABC and X-Wing rotorcraft with auxiliary propellers are again similar to the separate engine aircraft criteria. Propeller selections were made by General Electric and are summarized in Table 57. Engine performance was based on equivalent shaft horsepower (ESHP). Sensitivities similar to those obtained for the convertible VIGV engine aircraft were also determined.

TABLE 57. SELECTED PROPELLER CHARACTERISTICS

Rotorcraft	ABC	X-Wing
Prop Type	Conventional, Pusher	Prop Fan, Tractor
No. Props	1	2
Tip Speed, m/s (ft/sec)	229 (750)	244 (800)
Diameter, m (ft)	4.05 (13.3)	3.26 (10.7)
Cruise Altitude, m (ft)	3048 (10000)	9144 (30000)
Cruise Speed, km/h (kt)	463 (250)	741 (400)
Cruise Disc Loading, kW/m^2 (hp/ft^2)	142 (17.7)	230 (28.6)
Efficiency, %	88.5	82.7
Technology Base	Ref. 12	Ref. 13

ABC Rotorcraft With Propeller Propulsion

The ABC rotorcraft with propeller propulsion is basically identical to the separate engine configuration, except for the replacement of the fan engines by a single aft mounted pusher propeller. The propeller is driven by a shaft from the main gearbox and includes a speed-reduction gearbox in the tail cone as depicted in Figure 41A. The aircraft configuration is shown in 3-views in Figure 42.

The ABC propeller gearbox was sized to meet the power required at the cruise condition. A General Electric supplied propeller efficiency of 88.5% was used for the 4.05 m (13.3 ft diameter), 750 total activity factor propeller. The diameter was limited to 4.05 m (13.3 ft) to ensure adequate ground clearance when flareing.

Table 58 is a comparison of the sizing data for all ABC variants. The fuselage of the propeller configured aircraft is longer than the convertible VIGV aircraft due to the pusher propeller arrangement. As illustrated in Table 58, there are many similarities in the physical characteristics of the ABC aircraft. The prop aircraft offers a 2.4% reduction in gross weight compared to the VIGV aircraft. The weight empty of the prop aircraft is also slightly lower than the VIGV aircraft as shown in Table 59. The weight difference is accounted for primarily by the drive system (up 1.5% of gross weight), fuel (down 1.8% of gross weight), engines + prop

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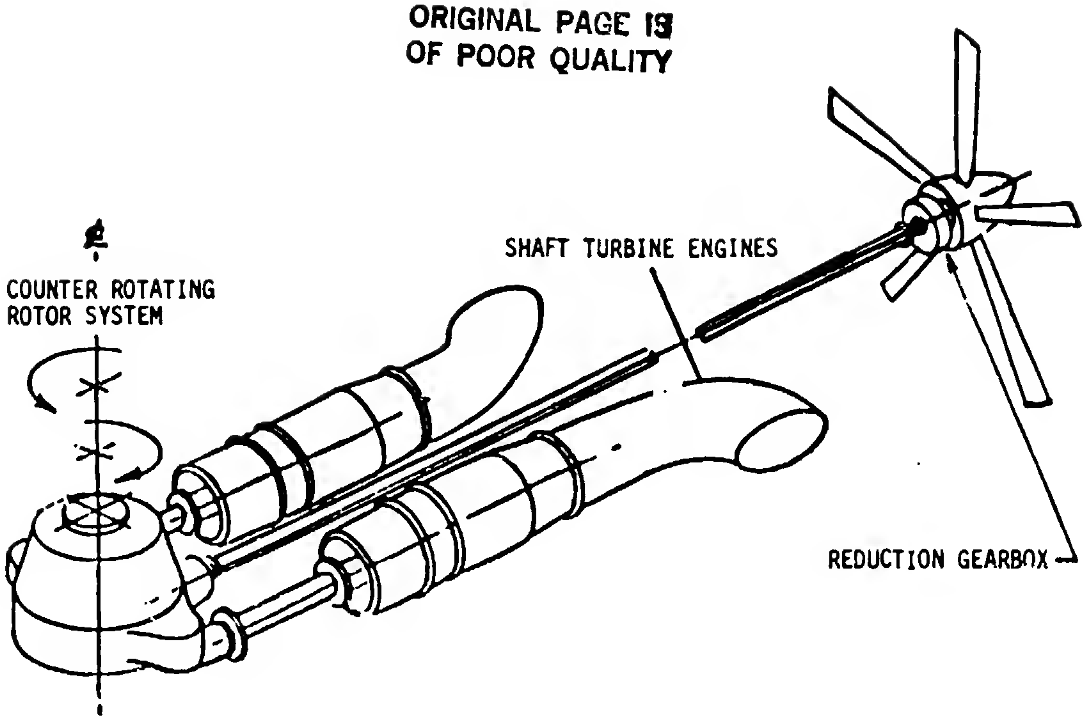

Figure 41A. ABC Propeller Drive System

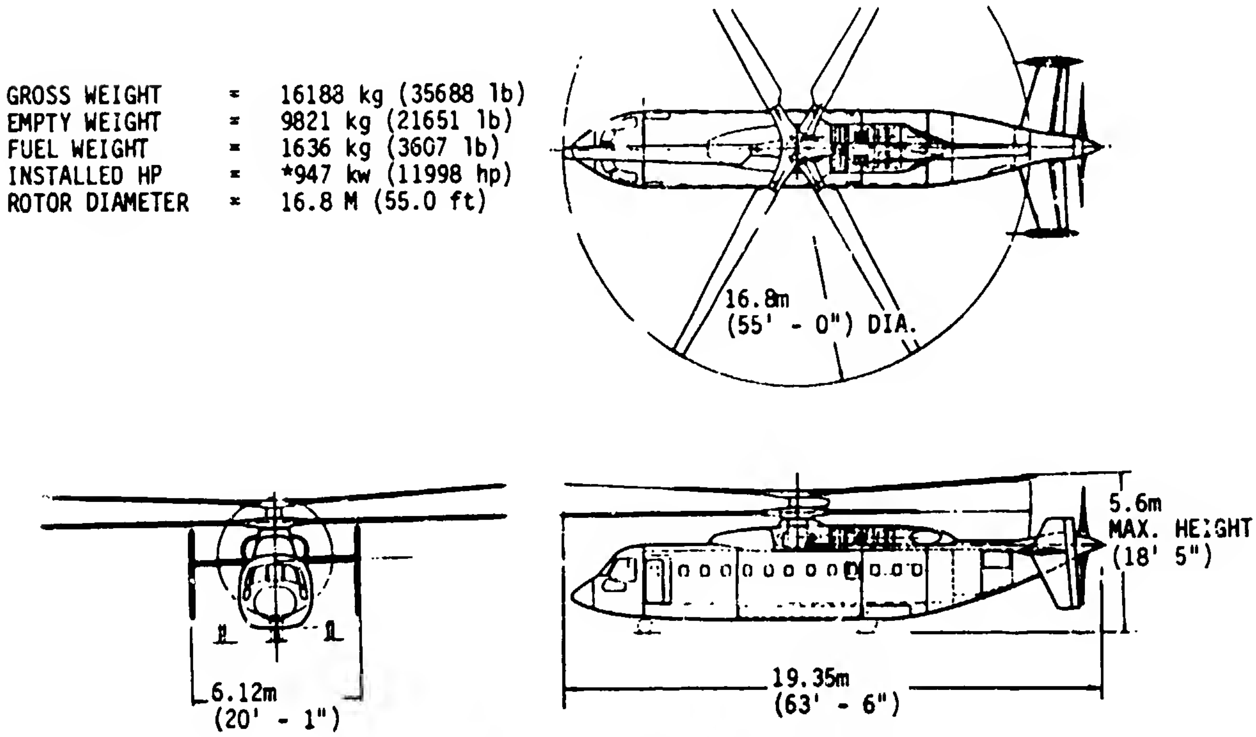

Figure 42. ABC Prop/Shaft Aircraft

TABLE 58. TASK I, II, AND III AIRCRAFT DESIGN COMPARISON			
	ABC Separate Engine Configuration	ABC Convertible Engine Configuration	ABC Propeller Configuration
Gross Weight, kg (lb)	17486 (38551)	16579 (36551)	16188 (35688)
Weight Empty, kg (lb)	10731 (23659)	9919 (21868)	9821 (21651)
Fixed Useful Load, kg (lb)	376 (830)	376 (830)	376 (830)
Payload, kg (lb)	4354 (9600)	4354 (9600)	4354 (9600)
Fuel Weight, kg (lb)	2024 (4462)	1929 (4253)	1636 (3607)
Fuselage Length, m (ft)	18.6 (60.9)	18 (59)	19.1 (62.5)
Fuselage Width, m (ft)	2.7 (8.7)	3 (10)	3 (10)
Horizontal Tail:			
Aspect Ratio	5.05	5.05	5.05
Span, m (ft)	6.0 (19.6)	5.8 (19.1)	5.7 (18.8)
Thickness/Chord	0.12	0.12	0.12
Mean Chord, m (ft)	1.2 (3.9)	1.2 (3.8)	1.1 (3.7)
Vertical Tail:			
Aspect Ratio	1.5	1.5	1.5
Span, m (ft)	3 (11.7)	3.6 (11.7)	3.6 (11.7)
Thickness/Chord	0.15	0.15	0.15
Mean Chord, m (ft)	2.4 (7.8)	2.4 (7.8)	2.4 (7.8)
Main Rotor:			
Diameter, Propeller, m (ft)	-	-	4.1 (13.3)
Diameter, Rotor, m (ft)	17.4 (57.2)	17.0 (55.7)	16.8 (55.0)
Solidity	0.1604	0.1604	0.1604
Disc Loading, kg/m^2 (lb/ft^2)	73 (15)	73 (15)	73 (15)
Tipspeed, m/s (ft/s)	204 (670)	204 (670)	204 (670)
Aerodynamic Data:			
Total Effective Flatplate Drag, m^2 (ft^2)	2.3 (24.9)	2.3 (24.3)	2.2 (24)
Total Wetted Area, m^2 (ft^2)	167 (1794)	164 (1762)	162 (1748)
Mean Skin Friction Coeff.	0.01388	0.01376	0.01371
Aircraft Efficiency Factor	0.88071	0.88071	0.88071

(down 1%), and airframe (down 1%). The large increase in drive system weight is due to the additional gearing and transmission elements required by the propeller. Based on the requirements, the maximum static sea level installed power was determined to be 4473 kw (5999 hp) per engine. The thrust-power split is determined in a manner similar to the separate engine or convertible VIGV configuration, except that thrust is now provided by a pusher propeller.

The high propeller cruise efficiency accounts for lower fuel burn as tabulated in Table 60. The lighter vehicle weight and low fuel burn of the propeller aircraft yield a low direct operating cost as illustrated in Figure 43. In comparison to the VIGV aircraft, the propeller configuration offers lower maintenance and depreciation costs on the powerplants but higher costs on the airframe and dynamic systems.

TABLE 59A. TASK I, II, AND III ABC WEIGHT BREAKDOWN - KILOGRAMS			
Engines	Separate	VIGV Fans	Prop/Shafts
Body	1633	1602	1548
Rotor	1450	1361	1296
Tail Surfaces	55	52	51
Tail Rotor	-	-	-
Landing Gear Group	655	631	607
Flight Controls	668	639	612
Fixed Equipment	2087	2087	2087
Vibration Absorbers	175	166	162
Turboshafts or Prop/Shafts			
Engines	1085	-	1063
Mounts and Pylons	23	-	23
Firewalls	12	-	12
Inlets, Cowling, and Exhaust	46	-	46
Controls	32	-	32
Starters	76	-	75
Turbofans or VIGV Fans			
Engines	738	1407	-
Mounts and Pylons	27	44	-
Firewalls	10	13	-
Inlets, Cowling, and Exhaust	43	146	-
Controls	32	32	-
Starters	51	98	-
Fuel System	219	208	177
PTO Gear	111	159	243
Prop(s) and Installation	-	-	351
Prop Gear	-	-	54
Prop Transmission	-	-	247
Misc. Gears and Shafts	1503	1274	1135
Weight Empty	10731	9919	9821
Crew	327	327	327
Trapped Liquids and Oil	50	50	50
Payload	4354	4354	4354
Fuel	2024	1929	1636
Gross Weight	17486	16579	16188

TABLE 59B. TASK I, II, AND III ABC WEIGHT BREAKDOWN - POUNDS			
Engines	Separate	VIGV Fans	Prop/Shafts
Body	3600	3531	3414
Rotor	3197	3000	2857
Tail Surfaces	121	115	112
Tail Rotor	-	-	-
Landing Gear Group	1445	1391	1338
Flight Controls	1473	1409	1350
Fixed Equipment	4600	4600	4600
Vibration Absorbers	386	366	357
Turboshafts or Prop/Shafts			
Engines	2392	-	2343
Mounts and Pylons	52	-	51
Firewalls	26	-	26
Inlets, Cowling, and Exhaust	102	-	102
Controls	70	-	70
Starters	167	-	166
Turbofans or VIGV Fans			
Engines	1627	3103	-
Mounts and Pylons	58	98	-
Firewalls	23	28	-
Inlets, Cowling, and Exhaust	95	321	-
Controls	70	70	-
Starters	114	217	-
Fuel System	482	459	390
PTO Gear	244	350	535
Prop(s) and Installation	-	-	774
Prop Gear	-	-	118
Prop Transmission	-	-	545
Misc. Gears and Shafts	3315	2810	2503
Weight Empty	23659	21868	21651
Crew	720	720	720
Trapped Liquids and Oil	110	110	110
Payload	9600	9600	9600
Fuel	4462	4253	3607
Gross Weight	38551	36551	35688

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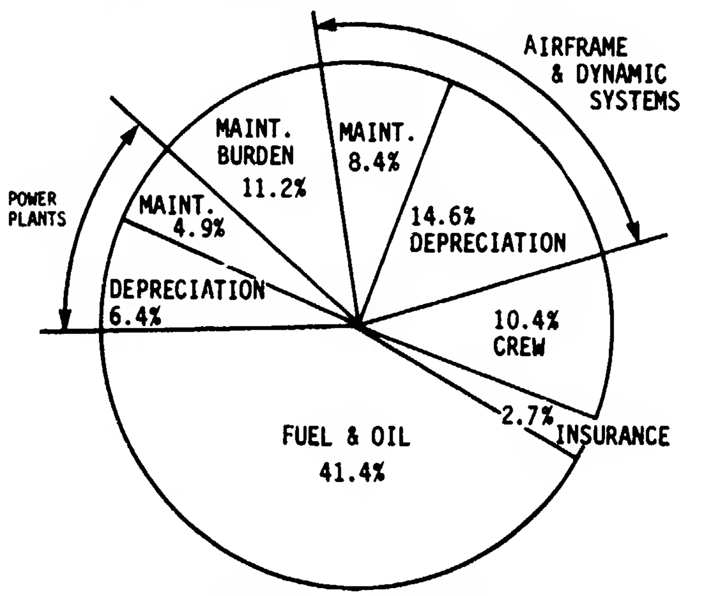
TABLE 60. AIRCRAFT FUEL BURNED SUMMARY - TASK I, II, AND III ABC ROTORCRAFT

	Fuel Burned, kg (lbm)					
	Separate Engines		Convertible Engines		Prop/Shaft Engines	
Design Mission						
Takeoff	57	(125)	65	(145)	50	(110)
Climb	72	(160)	150	(330)	48	(105)
Cruise	1268	(2795)	1123	(2475)	1032	(2275)
Reserve	626	(1380)	592	(1305)	508	(1120)
Total	2023	(4460)	1930	(4255)	1638	(3610)
Economic Mission						
Ground Handling and Takeoff	29	(65)	36	(80)	27	(60)
Climb	68	(150)	86	(190)	39	(85)
Cruise	1002	(2210)	896	(1975)	789	(1740)
Air Maneuver	39	(85)	36	(80)	36	(80)
Descent and Approach	39	(85)	50	(110)	23	(50)
Block Fuel	1177	(2595)	1104	(2435)	914	(2015)

370 km (200 nmi) MISSION, STD DAY, 65% LOAD FACTOR
$.524/1 (2.00/GALLON) FUEL, 1981 DOLLARS



TOTAL DOC = 8.3¢/ Seat.km
(15.4¢/ Seat - nmi)

Figure 43. ABC Propeller Configuration DOC Summary

ROTORCRAFT WITH PROP/SHAFT ENGINES - Continued

X-Wing Rotorcraft With Propeller Propulsion

Figure 44 illustrates the configuration changes required to replace the convertible engines with dual propeller propulsion. Due to the large size and high noise signature of the propellers, an aft mounted installation was selected.

Power from the two shaft turbine engines is combined in the main rotor gearbox and drives the compressors as well as the propellers. As in the baseline X-Wing, a clutch disengages the main rotor for conversion to cruise flight. Figure 45 illustrates the drive system arrangement.

The X-Wing propeller boxes were sized to meet the mission requirements with one propeller inoperative and a power limit equal to the hot day main transmission rating. The turboshaft engines provide a maximum of 10540 kW (14135 hp) each at sea level static conditions. Since the power required for maximum rate of climb exceeds the takeoff power required, the aircraft climbs on a torque limit. A propeller efficiency of 82.7% was used for the 3.26 m (10.7 ft) diameter prop-fans at an operating tip speed of 244 m/s (800 ft/sec.)

Sizing data for the prop configuration is tabulated in Table 61. The rear mounted tractor propeller arrangement increases the fuselage size and weight compared to the VIGV aircraft. Table 62 summarizes the weight breakdown for the three X-Wing variants. The gross weight increase of 9.7% for the prop/shaft powered aircraft over the VIGV powered comprises; airframe (+3.2% of gross weight), engine + props (+1.2%), drive system (+6.2%), and fuel (-0.8%). The largest increment in weight results from the additional drive train components necessary for propeller propulsion. The tail section is structurally reinforced to accommodate the higher loads. A reduction in mission fuel weight is due to the high cruise efficiency of the propellers. Note that the fuel burn summary shown in Table 63 shows that the cruise fuel is actually increased compared to the convertible aircraft. This is a result of the short, high-rate climb allowing the aircraft to spend more time at cruise. The low fuel burn enables the prop aircraft to have a direct operating cost only slightly higher than the VIGV configuration, despite the large weight increase. As shown in Figure 46, the more complicated airframe and dynamic systems contribute a larger proportion of operational costs then for the Task I and II rotorcraft.

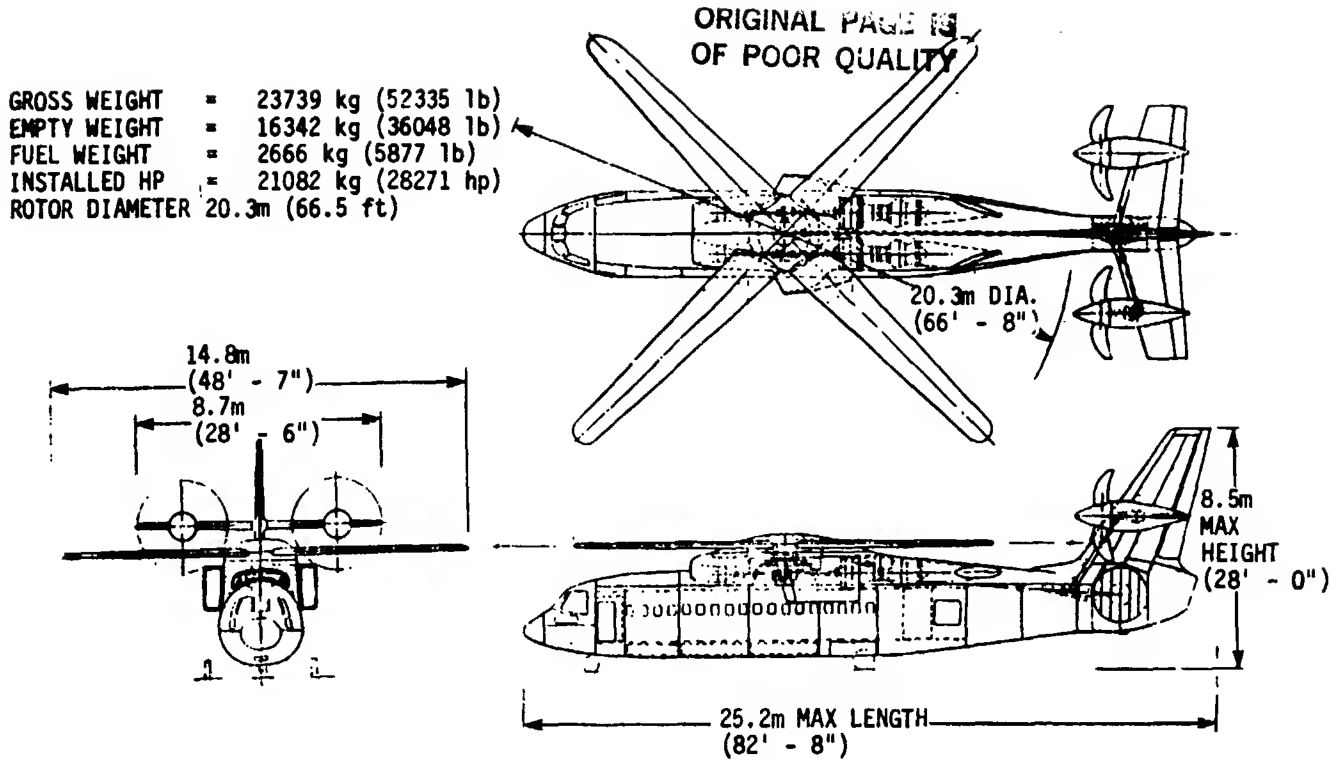


Figure 44. X-Wing Prop/Shaft Aircraft

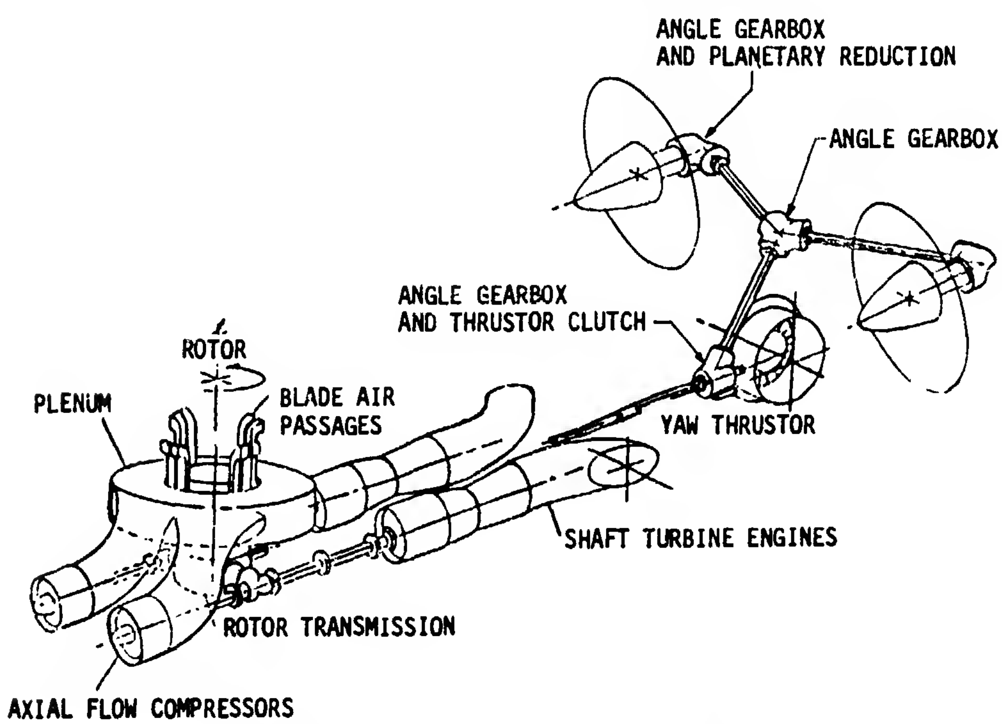


Figure 45. X-Wing Propeller Drive System

TABLE 61. AIRCRAFT DESIGN SUMMARY

	X-Wing Separate Engine Configuration	X-Wing Convertible Engine Configuration	X-Wing Propeller Configuration
Gross Weight, kg (lb)	25244 (55653)	21646 (47722)	23729 (52335)
Weight Empty, kg (lb)	17455 (38482)	14086 (31054)	16342 (36028)
Fixed Useful Load, kg (lb)	376 (830)	376 (830)	376 (830)
Payload, kg (lb)	4354 (9600)	4354 (9600)	4354 (9600)
Fuel Weight, kg (lb)	3058 (6741)	2830 (6238)	2666 (5877)
Fuselage Length, m (ft)	25 (82)	23 (76)	25.2 (82.6)
Fuselage Width, m (ft)	3 (10)	3 (10)	3 (10)
Horizontal Tail:			
Aspect Ratio	4.53	4.53	4.53
Span, m (ft)	7.9 (25.9)	7.0 (23.1)	7.6 (24.8)
Thickness/Chord	0.10	0.10	0.10
Mean Chord, m (ft)	1.7 (5.7)	1.6 (5.1)	1.7 (5.5)
Vertical Tail:			
Aspect Ratio	1.95	1.95	1.95
Span, m (ft)	4.6 (15.2)	4.1 (13.5)	4.4 (14.5)
Thickness/Chord	0.10	0.10	0.10
Mean Chord, m (ft)	2.3 (7.8)	2.1 (6.9)	2.2 (7.4)
Main Rotor/Wing:			
Area, m^2 (ft^2)	55.3 (594.8)	47.4 (510.0)	52.0 (559.3)
Diameter, Propeller, m (ft)	-	-	3.3 (10.7)
Diameter, Rotor, m (ft)	20.9 (68.7)	19.4 (63.6)	20.3 (66.5)
Solidity	0.1604	0.1604	0.1604
Disc Loading, kg/m^2 (lb/ft^2)	73 (15)	73 (15)	73 (15)
Rotor Tipspeed, m/s (ft/s)	198 (650)	198 (650)	198 (650)
Propeller Tipspeed, m/s (ft/s)	-	-	244 (800)
Aerodynamic Data:			
Total Effective Flatplate Drag, m^2 (ft^2)	1.58 (16.96)	1.46 (15.76)	1.53 (16.46)
Total Wetted Area, m^2 (ft^2)	308 (3315)	293 (3152)	297 (3202)
Mean Skin Friction Coeff.	0.00512	0.00517	0.00514
Aircraft Efficiency Factor	0.8251	0.8251	0.8251

TABLE 62A. TASK I, II, AND III X-WING WEIGHT BREAKDOWN - KILOGRAMS			
Engines	Separate	VIGV Fans	Prop/Shafts
Body	2459	2397	2426
Rotor	1842	1550	1767
Tail Surfaces	447	357	615
Tail Rotor	47	47	47
Landing Gear Group	947	812	890
Flight Controls	1193	1033	1126
Fixed Equipment	2214	2214	2214
Vibration Absorbers			
Turboshafts or Prop/Shafts			
Engines	2607	-	2190
Mounts and Pylons	57	-	48
Firewalls	21	-	21
Inlets, Cowling, and Exhaust	108	-	54
Controls	32	-	32
Starters	182	-	155
Turbofans or VIGV Fans			
Engines	1760	2381	-
Mounts and Pylons	74	60	-
Firewalls	16	17	-
Inlets, Cowling, and Exhaust	197	278	-
Controls	32	35	-
Starters	123	167	-
Fuel System	328	309	288
PTO Gear	218	294	355
Prop(s) and Installation	-	-	717
Prop Gear	-	-	337
Prop Transmission	-	-	641
Misc. Gears and Shafts	2306	1870	2174
Compressors	245	245	245
Weight Empty	17455	14086	16342
Crew	327	327	327
Trapped Liquids and Oil	50	50	50
Payload	4354	4354	4354
Fuel	3058	2829	2666
Gross Weight	25244	21646	23739

TABLE 62B. TASK I, II, AND III X-WING WEIGHT BREAKDOWN - POUNDS

Engines	Separate	VIGV Fans	Prop/Shafts
Body	5422	5285	5348
Rotor	4062	3416	3896
Tail Surfaces	985	786	1357
Tail Rotor	103	103	103
Landing Gear Group	2087	1790	1963
Flight Controls	2631	2278	2433
Fixed Equipment	4880	4880	4880
Vibration Absorbers			
Turboshafts or Prop/Shafts			
Engines	5747	-	4829
Mounts and Pylons	125	-	106
Firewalls	46	-	46
Inlets, Cowling, and Exhaust	237	-	118
Controls	70	-	70
Starters	402	-	342
Turbofans or VIGV Fans			
Engines	3880	52[illegible]	-
Mounts and Pylons	164	1[illegible]	-
Firewalls	35	38	-
Inlets, Cowling, and Exhaust	435	613	-
Controls	70	77	-
Starters	272	367	-
Fuel System	724	682	635
PTO Gear	481	649	784
Prop(s) and Installation	-	-	1580
Prop Gear	-	-	742
Prop Transmission	-	-	1414
Misc. Gears and Shafts	5084	4123	4792
Compressors	540	540	540
Weight Empty	38482	31054	36028
Crew	720	720	720
Trapped Liquids and Oil	110	110	110
Payload	9600	9600	9600
Fuel	6741	6238	5877
Gross Weight	55653	47722	52335

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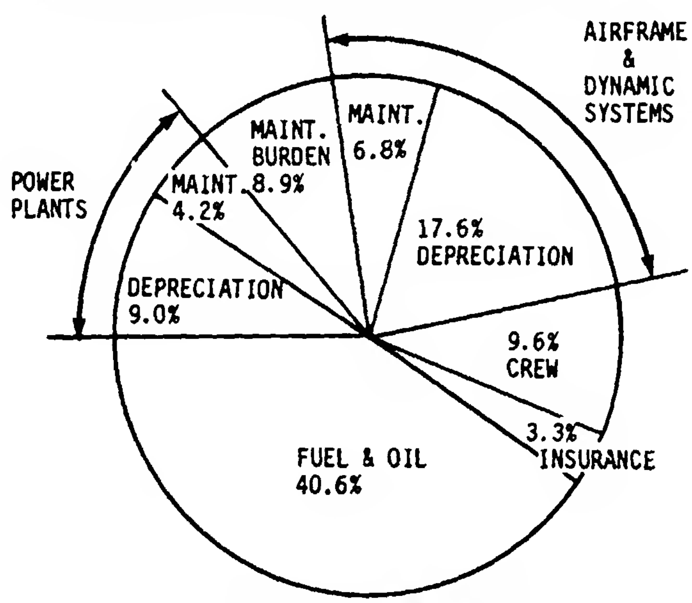
TABLE 63. AIRCRAFT FUEL BURNED SUMMARY - TASK I, II AND III X-WING ROTORCRAFT

	Fuel Burned, kg (lbm)					
Powerplant	Separate Engines		Convertible Engines		Prop/Shaft Engines	
Design Mission						
Takeoff	204	(450)	129	(285)	118	(260)
Climb	612	(1350)	522	(1150)	363	(800)
Cruise	1608	(3545)	1610	(3550)	1708	(3765)
Reserve	633	(1395)	569	(1255)	478	(1055)
Total	3057	(6740)	2830	(6240)	2667	(5880)
Economic Mission						
Ground Handling and Takeoff	109	(240)	77	(170)	73	(160)
Climb	515	(1135)	488	(1075)	336	(740)
Cruise	1254	(2765)	1211	(2670)	1229	(2710)
Air Maneuver	54	(120)	54	(120)	54	(120)
Descent and Approach	274	(605)	259	(570)	184	(405)
Block Fuel	2206	(4865)	2089	(4605)	1876	(4135)

822 km (450 nmi) MISSION, STD DAY, 85% LOAD FACTOR
$.593/1 ($2.25/GALLON FUEL, 1981 DOLLARS



TOTAL DOC = 8.7¢/ Seat km
(16.2¢/ Seat nmi)

Figure 46. X-Wing Propeller Configuration DOC Summary

COMPARISON OF TASK II AND TASK III ROTORCRAFT

ABC Rotorcraft

As stated in the summary (Table 64) the prop shaft engine had a 12.8% DOC advantage over the VIGV engine. The major contributor to this advantage is a 17% savings in block fuel due to the higher propulsive efficiency of the propeller vs. a fan as a thrust producer. A 2.4% savings in gross weight also helped to reduce DOC. This was achieved by merging the output of the two engines into a single transmission shaft driving one pusher propeller. The weight advantage would certainly have been lost if two propellers were used. The acquisition cost was also in favor of the prop shaft engine. This was the result of the cost advantage exhibited by production turboshaft engine and propeller components as compared to the development and startup costs still to come for VIGV engines.

Engine weight, price and maintenance expenses are all lower for the prop shaft engine as shown on Table 65. However, when the total propulsion system weight is compared on Table 66, the advantage of the prop shaft engine is greatly reduced with the weight actually showing the prop shaft engine system at a slight disadvantage (~3%). However, the aircraft gross weight is still able to show a 2.4% advantage for the prop shaft engine after taking account of the previously mentioned significant fuel savngs.

TABLE 64. MISSION ANALYSIS COMPARISON

Standard Day, 370 km (200 nmi) Mission

65% Load Factor, \$.528/l (\$2.00/gal) Fuel

1981 Economy

	Task II Convertible Engine	Task III Prop/Shaft Engine	% Change
Aircraft Gross Weight, kg (lbm)	16580 (36550)	16190 (35690)	-2.4
Aircraft Acquisition Cost \$ x 10^{-6}	7.99	7.13	-10.8
Block Fuel, kg (lbm)	1105 (2435)	915 (2015)	-17.3
Direct Operating Cost ¢/seat·km (¢/seat·nmi)	9.5 (17.7)	8.3 (15.4)	-12.8

TABLE 65A. COMPARISON OF CONVERTIBLE AND PROP/SHAFT ENGINES ABC ROTORCRAFT

SI Units

Mission Size, 1981 Economy

	Task II Convertible Engine	Task III Prop/Shaft Engine
Aircraft Goss Weight, kg	16580	16190
ISA +15°C OEI Power, kW	3885	3795
Design Cruise 3048 m, 463 km/h, ISA +10°C		
Output Power, kW	1335	-
Thrust, N	7985	-
Equivalent Power, kW	-	2645
Fuel Flow, kg/h		
ISA, Normal Takeoff	750	515
ISA, Mid Cruise	695	565
Powerplant Weight, kg	760	530
Powerplant Price, $ x 10^{-6}	1.53	0.90
Powerplant Maintenance, $/hr	54.00	39.00
Propeller Weight, kg (2 engines drive single pusher propeller)	-	350

TABLE 65B. COMPARISON OF CONVERTIBLE AND PROP/SHAFT ENGINES ABC ROTORCRAFT

English Units

Mission Size, 1981 Economy

	Task II Convertible Engine	Task III Prop/Shaft Engine
Aircraft Gross Weight, lbm	36550	35690
ISA +27°F OEI Power, hp	5210	5090
Design Cruise 10000 ft, 250 kt, ISA +18°F		
Output Power, hp	1790	-
Thrust, lbf	1795	-
Equivalent Power, hp	-	3545
Fuel Flow, lbm/hr		
ISA, Normal Takeoff	1650	1135
ISA, Mid Cruise	1535	1250
Powerplant Weight, lbm	1670	1175
Powerplant Price, $ x 10^{-6}	1.53	0.90
Powerplant Maintenance, $/hr	54.00	39.00
Propeller Weight, lbm (2 engines drive single pusher propeller)	-	775

TABLE 66. AIRCRAFT WEIGHT COMPARISON TASK II AND TASK III ABC ROTORCRAFT				
	Task II		Task III	
	Convertible Engines		Prop/Shaft Engine	
	kg	(lbm)	kg	(lbm)
Convertible Engines	1410	(3105)	-	-
Turboshaft Engines	-		1065	(234[illegible])
Propeller	-		350	(770)
Installation	330	(735)	190	(420)
Drive System	1435	(3160)	1680	(3700)
Propulsion Sub Total	3175	(7000)	3285	(7235)
Airframe	2285	(5035)	2205	([illegible]65)
Main Rotor	1360	(3000)	1295	([illegible])
Equipment and Controls	3100	(6835)	3035	([illegible])
Crew and Payload	4730	(10430)	4730	(10430)
Fuel	1930	(4250)	1640	(3615)
Gross Weight	16580	(36550)	16190	(35690)

X-Wing Rotorcraft

The significant advantage shown for the prop shaft engine in the ABC rotorcraft configuration is seriously compromised when the same comparison is made for the X-Wing rotorcraft. As shown on Table 67 the DOC advantage is only 1.1% with only the block fuel comparison showing a 10.2% advantage for the prop shaft engine. This is less than the advantage of the ABC rotorcraft probably due to the lower propulsive efficiency of a prop fan at the higher X-Wing flight speeds.

Similarly, the prop fan required for the high flight speeds of the X-Wing rotorcraft as compared to a standard propeller is responsible for the higher acquisition cost. There are still substantial development costs to come for prop fans and the cost per unit will be in the startup region of a standard learning curve for some time to come.

Also, the necessity to depart from the single propulsor design employed on the ABC rotorcraft has had a deleterious effect. Whereas the engine weight, price and maintenance values on Table 68 show an advantage for the prop shaft engine, the total propulsion system now shows a 30% disadvantage when two prop fan/drive systems are utilized. In fact, the aircraft gross weight continues to show a 9.7% disadvantage for the prop fan engine even after accounting for the lower fuel weight flows indicated on Tables 68 and 69.

TABLE 67. MISSION ANALYSIS COMPARISON, TASK II AND TASK III X-WING ROTORCRAFT

Standard Day, 835 km (450 nmi) Mission

85% Load Factor, \$.594/l (\$2.25/gal) Fuel

1981 Economy

	Task II Convertible Engines	Task III Prop/Shaft Engines	% Change
Aircraft Gross Weight, kg	21650	23740	+9.7
(lbm)	(47720)	(52335)	
Aircraft Acquisition Cost, \$ x 10^{-6}	11.2	11.9	+6.1
Block Fuel, kg	2090	1876	-10.2
(lbm)	(4605)	(4135)	
Direct Operating Cost ¢/seat·km	8.7	8.7	+0.6
(¢/seat·nmi)	(16.1)	(16.2)	

TABLE 68A. COMPARISON OF CONVERTIBLE AND PROP/SHAFT ENGINES X-WING ROTORCRAFT

SI Units

Mission Size, 1981 Economy

	Task II Convertible Engine	Task III Prop/Shaft Engine
Aircraft Gross Weight, kg	21650	23740
ISA +15°C OEI Power, kW	8055	8920
Design Cruise, 9144 m, 741 km/h, ISA +10°C		
Output Power, kW	255	-
Thrust, N	1[illegible]475	-
Equivalent Power, kW	-	3250
Fuel Flow, kg/h		
ISA, Normal Takeoff	1550	1265
ISA, Mid Cruise	810	715
Powerplant Weight, kg	1190	[illegible]
Powerplant Price, \$ x 10^{-6}	2.22	1.74
Powerplant Maintenance, \$/hr	67.00	56.00
Propfan Weight, kg	-	360

TABLE 68B. COMPARISON OF CONVERTIBLE AND PROP/SHAFT ENGINES X-WING ROTORCRAFT

English Units

Mission Size, 1981 Economy

	Task II Convertible Engine	Task III Prop/Shaft Engine
Aircraft Gross Weight, lbm	47720	52335
ISA +27°F OEI Power, hp	10800	11960
Design Cruise 30000 ft, 400 kt ISA +18°F		
Output Power, hp	340	-
Thrust, lbf	2580	-
Equivalent Power, hp	-	4360
Fuel Flow, lbm/hr		
ISA, Normal Takeoff	3420	2790
ISA, Mid Cruise	1790	1575
Powerplant Weight, lbm	2625	2415
Powerplant Price, $ x 10^{-6}	2.22	1.74
Powerplant Maintenance, $/hr	67.00	56.00
Propfan Weight, lbm	-	790

TABLE 69. AIRCRAFT WEIGHT COMPARISON, TASK II AND TASK III ROTORCRAFT

	Task II Convertible Engines kg	Task II Convertible Engines (lbm)	Task III Prop/Shaft Engines kg	Task III Prop/Shaft Engines (lbm)
Convertible Engines	2380	(5250)	-	-
Turboshaft Engines	-		2190	(4830)
Propfans	-		715	(1580)
Installation	575	(1270)	310	(680)
Drive System	2170	(4775)	3505	(7730)
Propulsion Sub Total	5125	(11295)	6720	(14820)
Airframe	3615	(7965)	3980	(8770)
Main Rotor	1550	(3415)	1770	(3900)
Equipment and Controls	3800	(8375)	3875	(8540)
Crew and Payload	4730	(10430)	4730	(10430)
Fuel	2830	(6240)	2665	(5875)
Gross Weight	21650	(47720)	23740	(52335)

ADVANCED TECHNOLOGY OPTIONS

The purpose of this Task was to evaluate advanced technology options which could benefit ABC or X-Wing rotorcraft propulsion systems. Two features were investigated; an internal clutch in the VIGV turbofan and a traction drive in place of a main rotor transmission.

1. The internal clutch is used to disengage the fan from the LP system in the turboshaft mode at takeoff. Its purpose is to eliminate the windage losses of the bypass panel rotating at high speed with VIGV closed. It also eliminates potential noise and turbulence related problems related to this operating condition.

2. Traction drives are a novel approach to reducing the weight of larger speed ratio transmissions over geared transmissions.

Traction Drive

Although traction drives have been used for a long time, all the applications have been in relatively small sizes. As traction drives are only applicable to coaxial shafting systems the most likely utilization of a traction drive in a helicopter or rotorcraft would be in the main rotor reduction gear. This gear would probably be a hybrid geared traction drive with a bevel gear reduction input followed by a further reduction in a planetary traction drive. A design study of such a system is given in a paper "Hybrid Geared Traction Transmissions" by A.L. Nasvytis and G. White which was presented at the NASA Power Transmission Conference held in Cleveland in June 1981. The maximum horsepower considered in this study was 3000 which is considerably less than that required for an ABC or X-Wing rotorcraft. Therefore, to obtain more definitive conclusions for this study, a detailed design study of a particular case would be required, and this was considered to be beyond the scope of the contract. However, certain observations about a traction drive for this application may be ventured:

1. A traction drive would show a weight advantage over a geared planetary reduction gear at higher reduction ratios in the coaxial system. If the ratio per planetary stage is greater than about 3.8:1, then the traction drive should show a weight advantage.

2. By taking a larger reduction ratio in the main gearbox, some savings on other system gearboxes and shafting should be attained.

3. The housing diameter for a planetary traction drive would be larger, especially at higher ratios, and the housing length would be shorter.

4. The traction drive is complicated by the required torque loading system, but would require fewer bearings than a multi-stage geared planetary system.

5. Any replacement of a geared system by a traction drive should reduce noise and vibration.

6. In the traction drive there will be some creep or slippage in output speed with load.

7. The traction drive provides the possibility of a variable gear ratio, which would be useful for ABC cruise conditions where rotor tip speed is now limiting.

Table 70 lists the advantages and disadvantages of traction drives. It is not thought that any advantage could be obtained by using traction drives in the engine accessory gearbox.

TABLE 70. TRACTION DRIVE - TASK III

	Advantages	Disadvantages
Weight	Lower*	
Production Cost		Expected to be higher.
Development Cost		Higher and longer development time
Durability	Same	Same .
Non-Synchronous (Slip)		Some variable slip.
Variable Gear Ratio	Feasible	
Diameter		Larger housing.
Length	Shorter	
Bevel Gear Application		Not feasible.
Noise	Lower than all-geared system	
Vibration	Lower	
Experience in Size		None .
Complexity		Needs torque loading system.

*Assumes a 3.8:1 or greater planetary reduction:
Helicopter rotor reduction systems greater than 3.8:1.
Turbofan engine internal gearing less than 3.8:1.

TASK III - ALTERNATIVE CONVERTIBLE POWERPLANT CONFIGURATIONS AND TECHNOLOGIES - Continued

COMPARISON OF TASK II AND TASK III ROTORCRAFT - Continued

ADVANCED TECHNOLOGY OPTIONS

Fan Rotor Clutch

In one configuration option of the VIGV fan type convertible engine, power is supplied to the fan rotor through a clutch while power to the vehicle rotor is delivered through a direct drive power train (shown schematically in Figure 47). In this system, the fan rotor is declutched (free wheeling) in all operational modes where forward thrust augmentation is not a flight requirement. (Shaft mode of operation). When forward thrust augmentation is desired (fan mode of engine operation) the clutch is engaged and the fan rotor accelerated to LP turbine speed.

Principal advantage to be gained by the use of a clutch is the elimination of fan parasitic drag power and a resulting decrease in fuel consumed during shaft mode operation.

Adding a clutch to a VIGV engine is a tradeoff between reduced fan windage and reduced cycle pressure ratio at hover. Because of the lower cycle pressure ratio at the hover sizing condition, core size is 10 to 15% bigger with a clutch, although fan size is virtually unchanged. This bigger core is under-utilized at cruise, relative to the core of the clutch-less engine, resulting in a cruise SFC penalty of 2 to 3% (which overwhelms the takeoff fuel saving) (see Table 71).

Other disadvantages attributed to the clutch system include increased weight, acquisition costs, system complexity and program risk. Increased risk is associated with the program requirement to develop a clutch suitably integrated into the engine design to meet the high reliability and low maintenance requirements essential to competitive commercial aircraft operations. Another possible advantage of the clutch lies in reducing fan noise at takeoff to virtually zero.

Although the clutch does not show a payoff in the assumed missions used for this study, it can show a payoff in a mission with more time spent operating in the turboshaft mode. The break-even point from a fuel consumption standpoint is a mission with about 15% of the time spent at hover.

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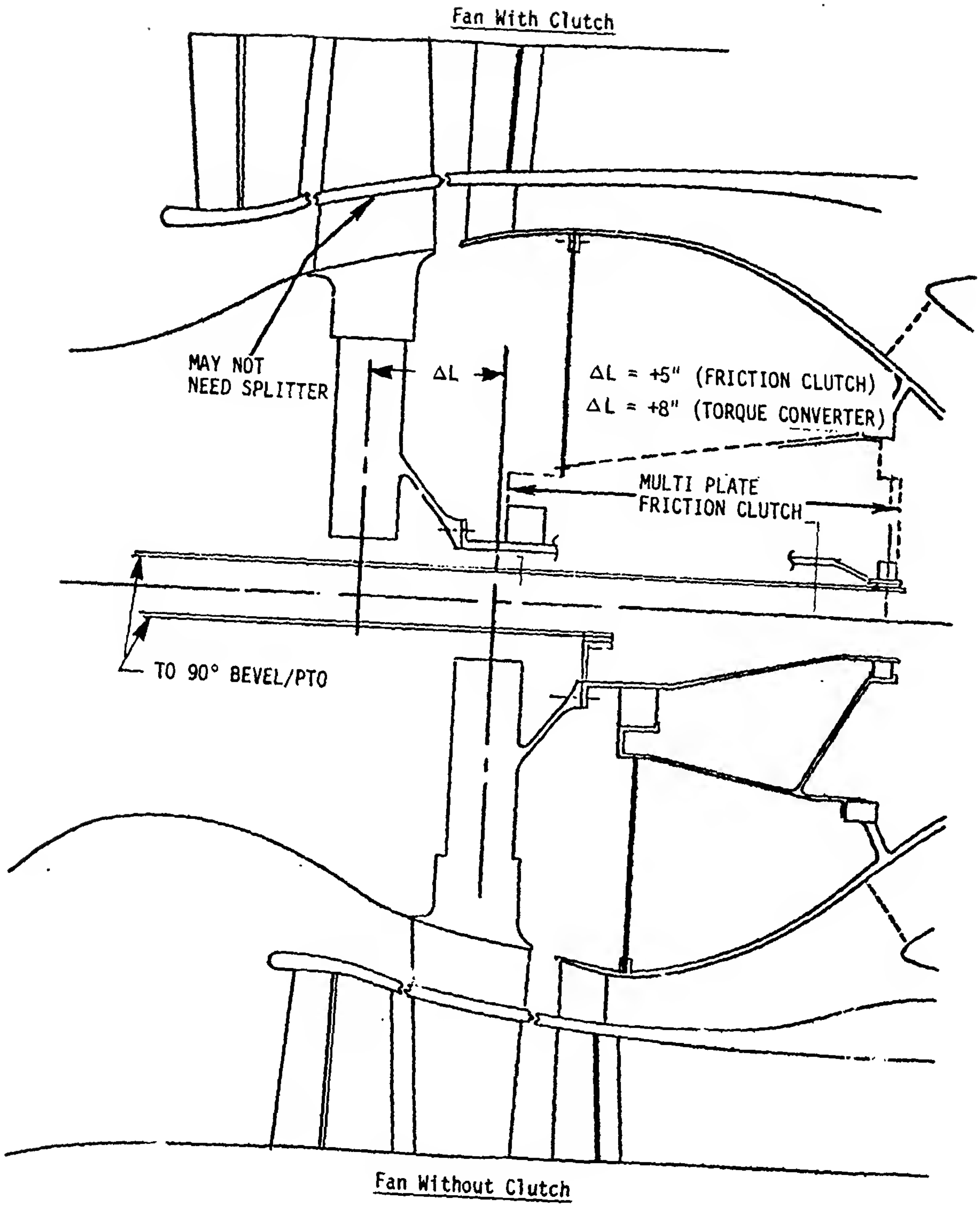

Figure 47. Fan Rotor with Clutch (Top View) and Without Clutch (Bottom View)

TABLE 71. CLUTCH EVALUATION IN VIGV CONVERTIBLE ENGINE FOR ABC ROTORCRAFT

	Advantages	Disadvantages
Fan Decoupled at Takeoff	No windage power loss	Loss of fan hub supercharging of core
	Reduced need for far closed VIGV and VEGV operation	
Core Size		10 to 15% larger. Net effect of above.
		Under-utilized at all conditions except OEI.
Weight		+ 54 to 68 kg (120 to 150 lb) for clutch
		+ 45 to 68 kg (100 to 150 lb) for core size
		Net increase of 100 to 136 kg (220 to 300 lb)
Price		+120 to 150 K$ for clutch
		+90 to 140 K$ for core size
		+210 to 290 K$ net
Fuel Consumption	=15 to 20% at takeoff	+2 to 3% at cruise
Noise	No fan noise at takeoff	

TASK IV

ENGINE CYCLING AND STAGING ARRANGEMENT

TASK IV - ENGINE CYCLE AND STAGING ARRANGEMENT

Baseline convertible VIGV turbofan engines were selected in Task II for the ABC and X-Wing rotorcraft based on prior General Electric design experience. In Task IV, parametric variations in these baseline cycles were evaluated for their impact on aircraft economics and fuel useage.

The study involved three categories or variations:

1. Fan pressure ratio was varied while holding overall cycle pressure ratio and turbine inlet temperature (T41) constant.
2. Overall cycle pressure ratio and T41 were varied while holding fan pressure ratio constant.
3. Separate flow and mixed flow exhaust systems were directly compared, holding the other parameters constant.

FAN PRESSURE RATIO TRENDS

Design and Evaluation Method

A family of VIGV turbofan point designs were defined for each rotocraft. The designs were selected to cover the range of the fan pressure ratio under investigation, and to evaluate both mixed and separate flow exhaust. Configuration changes were incorporated as appropriate. For example, geared fan designs were used for the lowest fan pressure ratios, and booster stages were added to the fan hub as required to maintain constant overall cycle pressure ratio. Tables 72 and 73 summarize the engines studied for the ABC and X-Wing, respectively. All of these engines share the baseline core design; a 5+1 axi-centrifugal compressor driven by a two stage turbine.

The convertible engines within each family were sized to a constant net OEI hover power on a SLS +15°C (27°F) day. The fuel consumption characteristics of the engines were evaluated at the initial cruise condition. The initial cruise point was 3048 m, 463 km/h, ISA +10°C (10000 ft, 250 kt, ISA +18°F) for the ABC turbofans and 9144 m, 741 km/h, ISA +10°C (30000 ft, 400 kt, ISA +18°F) for the X-Wing turbofans. The nacelle drags were obtained by using formulac supplied by Boeing Vertol which gave the nacelle drag as a function of total corrected fan flow (assuming constant nacelle to fuselage spacing). It should be noted that the same drag formulae were used for both mixed and separate flow exhaust installations as an approximation.

The engines within each family were compared to baseline cases which were fundamentally the same as the Task II VIGV engines; the 1.36 fan pressure ratio engine for the ABC and the 1.65 fan pressure ratio engine for the X-Wing.

Engine weight, price, and maintenance costs were derived by scaling major subassemblies using the pertinent sizing parameters from the cycle results (primarily fan and core airflow) and adjusting for configuration differences. These engine trends were used with the Boeing Vertol mission merit factor sensitivities to determine the rotorcraft gross weight, mission fuel, and DOC trends.

TABLE 72. ENGINE CONFIGURATIONS FOR FAN PRESSURE RATIO TREND STUDY ABC ROTORCRAFT

100% Corrected Fan Speed

Constant Cycle Pressure Ratio and Max T41

Fan Bypass Pressure Ratio	1.18	1.25	1.36	1.50	1.65	1.36
Exhaust Type	Sep	Sep	Sep	Sep	Sep	Mixed
Exhaust Vel. Ratio	1.0 →					NA
Geared/Direct Drive	Geared	Geared	Direct →			
Fan Bypass Ratio	7.6	5.5	3.9	2.8	2.1	2.8
Overall Cycle Pressure Ratio	25.1 →					
No. of Booster Stages	1	1	1	1	0	1
No. of LPT Stages	3	3	5	4	3	4
Max T41, °C (°F)	1288 (2350) →					
Δ% Total Corrected Fan Flow	+66	+28	Base	-18	-30	-22
Δ% Corrected Core Flow	-5.7	-4.6	Base	+5.2	+7.4	+1.4

TABLE 73. ENGINE CONFIGURATIONS FOR FAN PRESSURE RATIO TREND STUDY X-WING ROTORCRAFT

100% Corrected Fan Speed

Constant Cycle Pressure Ratio and Max T41

Fan Bypass Pressure Ratio	1.36	1.50	1.65	1.75	1.65
Exhaust Type	Mixed →				Sep
Exhaust Vel. Ratio	NA →				1.35
Geared/Direct Drive	DD →				
Fan Bypass Ratio	5.6	3.8	2.8	2.3	3.3
Overall Cycle Pressure Ratio	25.2 →				
No. of Booster Stages	1	1	0	0	0
No. of LPT Stages	5	4	3	2	3
Max T41 °C (°F)	1288 (2350) →				
Δ% Total Corrected Fan Flow	+66	+25	Base	-12	+31
Δ% Corrected Core Flow	-4.7	-1.0	Base	+2.0	+13

FAN PRESSURE RATIO TRENDS - Continued

ABC Fan Pressure Ratio Trends - Discussion of Results

The results of the study are given in Figures 48-51. As fan pressure ratio is increased, the bypass ratio and the total fan flow decrease, while the core flow increases. The magnitude of the change in fan flow is greater than that of the core flow. Weight and price decrease with increasing fan pressure ratio due to the significant reduction in fan flow and the absence of reduction gears for the higher fan pressure ratio cases (see Figure 48). The engine price is directly influenced by the engine weight, but the slope is not as pronounced because the core, which is an expensive part of the engine, is increasing in size.

Figure 49 demonstrates that the initial cruise fuel flow and the engine maintenance increase with rising fan pressure ratio. The maintenance trend slope reverses from the engine weight or price. This is due to the high core maintenance cost (core flow is increasing with fan pressure ratio) overwhelming the decreasing LPT spool maintenance. The cruise fuel flow (including the effect of nacelle drag shown on Figure 51) increases with fan pressure ratio, which is the expected result for decreasing bypass ratio.

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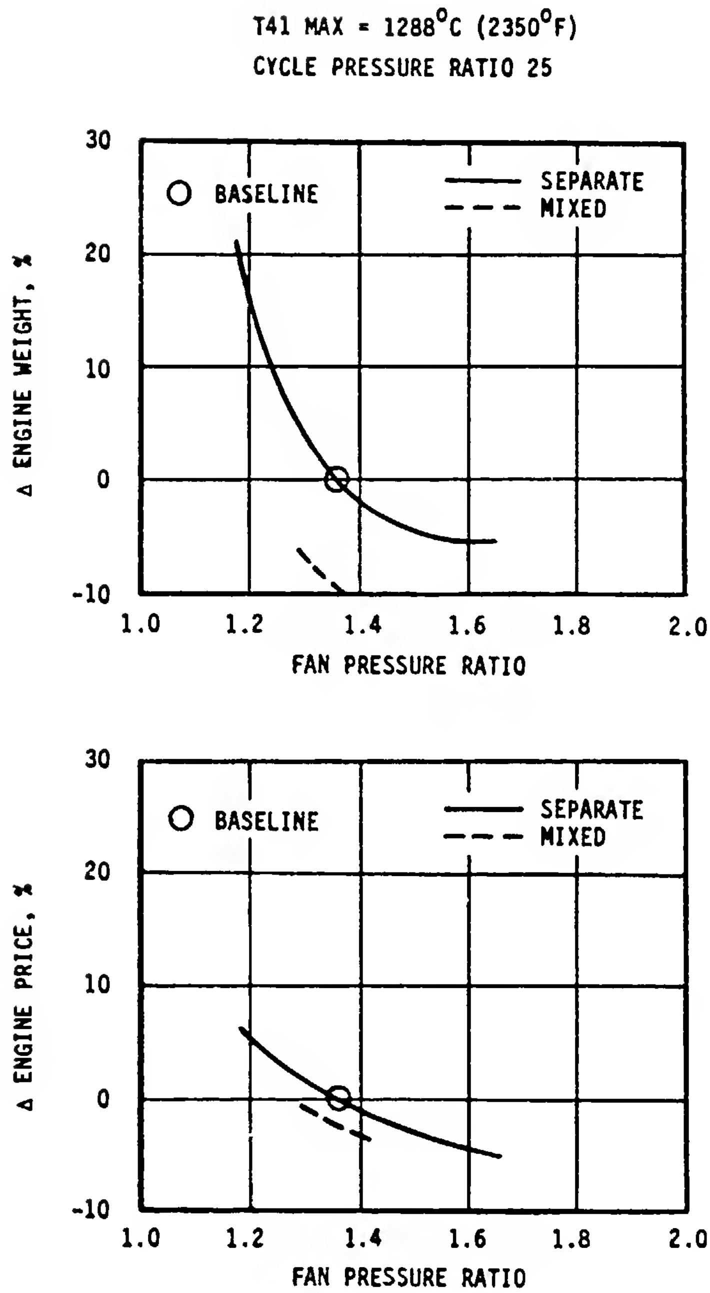

Figure 48. VIGV Engine Pressure Ratio Tr[illegible]ds Engine Weight and Engine Price - ABC Rotorcraft

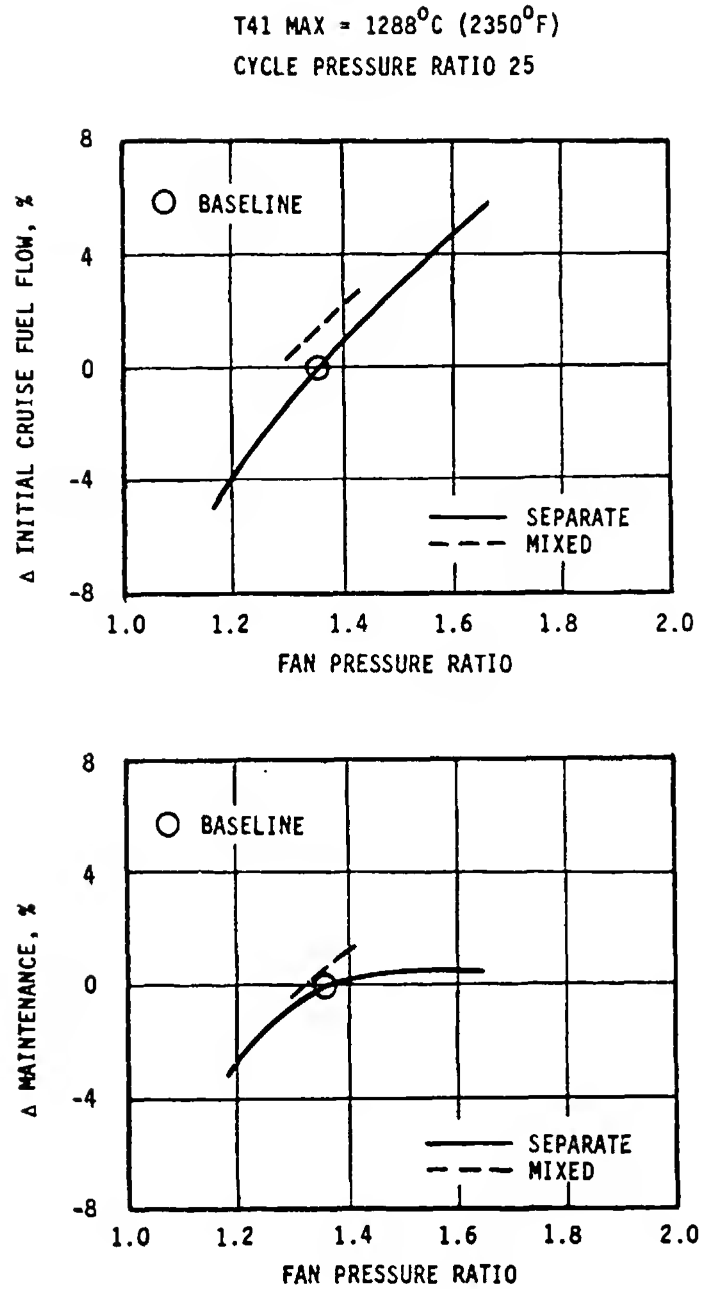

Figure 49. VIGV Engine Pressure Ratio Trends Fuel Flow and Maintenance - ABC Rotorcraft

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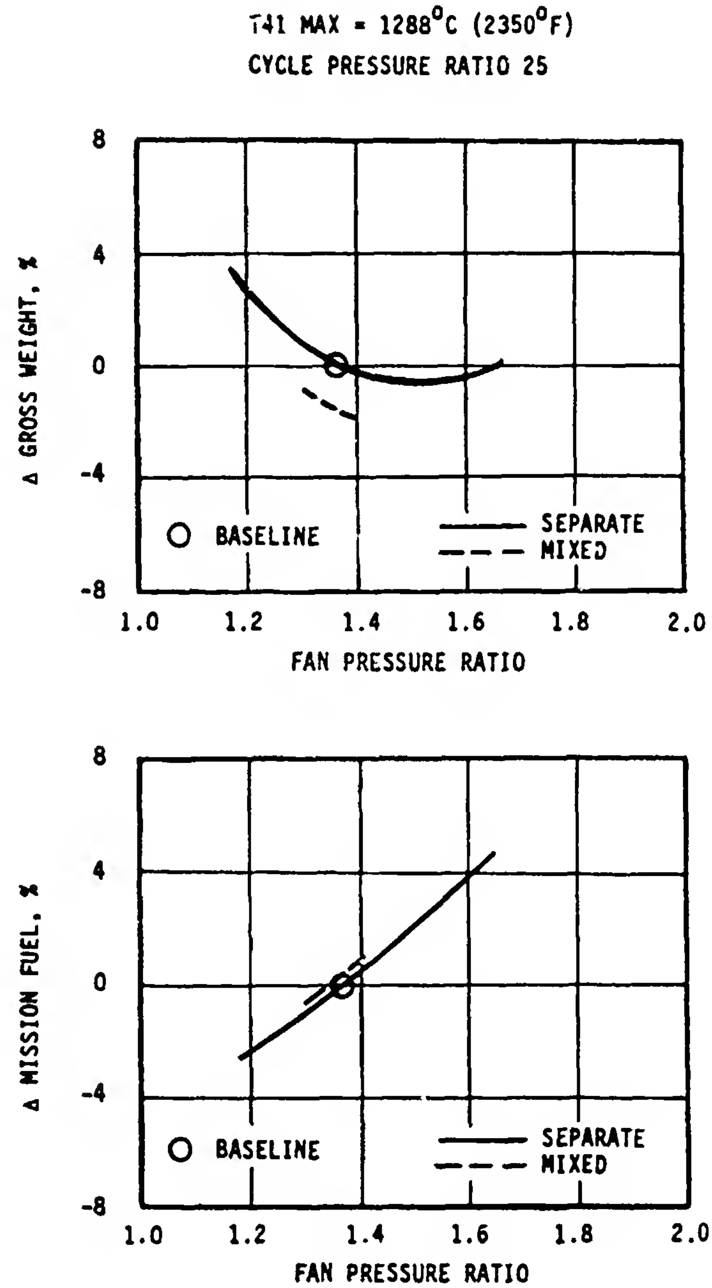

Figure 50. VIGV Engine Pressure Ratio Trends Gross Weight and Mission Fuel - ABC Rotorcraft

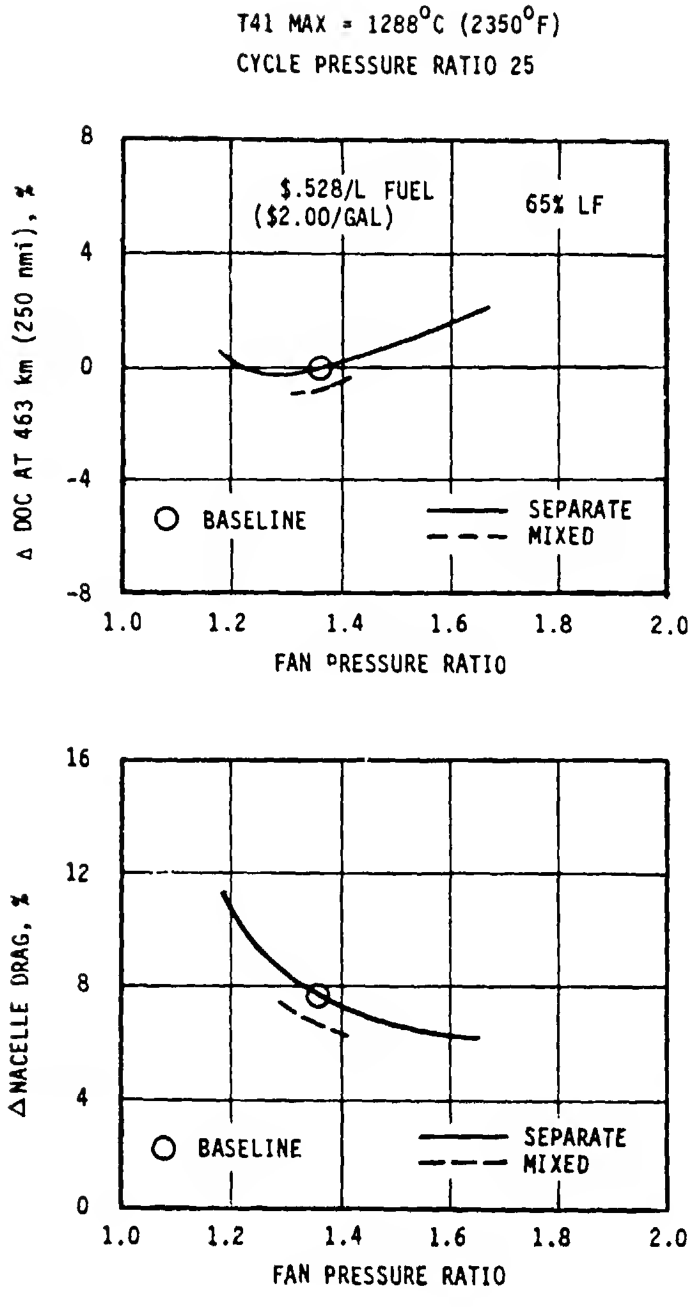

Figure 51. VIGV Engine Pressure Ratio Trends DOC and Nacelle Drag - ABC Rotorcraft

FAN PRESSURE RATIO TRENDS - Continued

In Figure 50, the gross weight curve does not fall as sharply as the engine weight curve because decreasing engine weight and increasing initial cruise fuel flow have counter balancing effects on the gross weight trend. The gross weight reaches a minimum near a fan pressure ratio of 1.5.

Mission fuel flow is also influenced by the same contrary effects of engine weight and cruise fuel, but in this case the initial cruise fuel flow dominates.

The DOC result for the ABC VIGV turbofans is shown in Figure 51 for the standard day, 65% load factor, 463 km (250 nmi) mission with fuel at $.528/l ($2.00/gal). The fan pressure ratio for minimum DOC is 1.3, but shows a very small advantage over the original 1.36 fan pressure ratio baseline.

Mixed versus Separate Exhaust: A mixed flow case with the same fan pressure ratio as the baseline engine was also analyzed. As given in Tables 72 and 73, the fan flow for the mixed exhaust engine is 22% less and the core flow 1.4% more than for the separate flow engine. The mixed exhaust engine results have been given in Figures 48-51. The engine weight is much less for the mixed exhaust case due to the reduction in fan flow, while the engine price is closer to the separate case due to the increase in core flow and the price of the mixer. The initial cruise fuel flow and maintenance cost (due to the larger core) are greater for the mixed exhaust engine. Using the mission trade factors, the gross weight favors the mixed exhaust while the mission fuel favors the separate exhaust. The net DOC result is that using a mixed exhaust instead of a separate exhaust at this fan pressure ratio would result in a net decrease of 0.6% in DOC. However, if nacelle weight and price differences between mixed and separate flow were included, the mixed flow DOC advantage would be eroded. Prior studies indicated that for such a cycle (high bypass ratio and low fan pressure ratio), the payoff of using a mixed flow case would not be great.

X-Wing Fan Pressure Ratio Trends

The engine cycles of the X-Wing VIGV turbofans were given in Table 73. Results are summarized in Figures 52 through 55. The changes in bypass ratio, fan flow and core flow are consistent with the behavior of the ABC engines, although the magnitudes are different. Figure 52 demonstrates that the trends of X-Wing engine weight and engine price are also similar to the corresponding ABC trends.

The initial cruise fuel flow shown in Figure 53 represents the series of engines with constant OEI hover power and taking nacelle drag effects into account. For the installed engines, the higher drags (as shown in Figure 55) of the lower fan pressure ratio engines partially counteract the propulsive efficiency benefit of lower fan pressure ratio.

X-Wing maintenance, Figure 53, decreases with rising fan pressure ratio. This behavior is contrary to the ABC turbofans because the core items are not as great a percentage of maintenance in the higher bypass ratio X-Wing turbofans.

As in the case of the ABC, the X-Wing gross weight and mission fuel trends. Figure 54, are the result of the counterbalancing effects of engine weight and fuel consumption. Engine weight exerts the dominant effect on gross weight, but the two nearly balance in their impact on mission fuel, resulting in an optimum at a fan pressure ratio of 1.6.

The X-Wing DOC result (Figure 55) for standard day, 85% load factor, 833 km (450 nmi), $.594/l fuel ($2.25/gal) indicates that using a fan pressure ratio higher than the baseline will yield a somewhat lower DOC. However, the slope of the DOC curve is decreasing and there is only 0.2% DOC to be gained by operating at a fan pressure ratio of 1.75 vs. the baseline. The discrepancy between the X-Wing and ABC DOC curves is primarily cuased by the larger (.24% DOC/% Engine Weight) X-Wing sensitivity to engine weight than for the ABC (.14% DOC/% Engine Weight).

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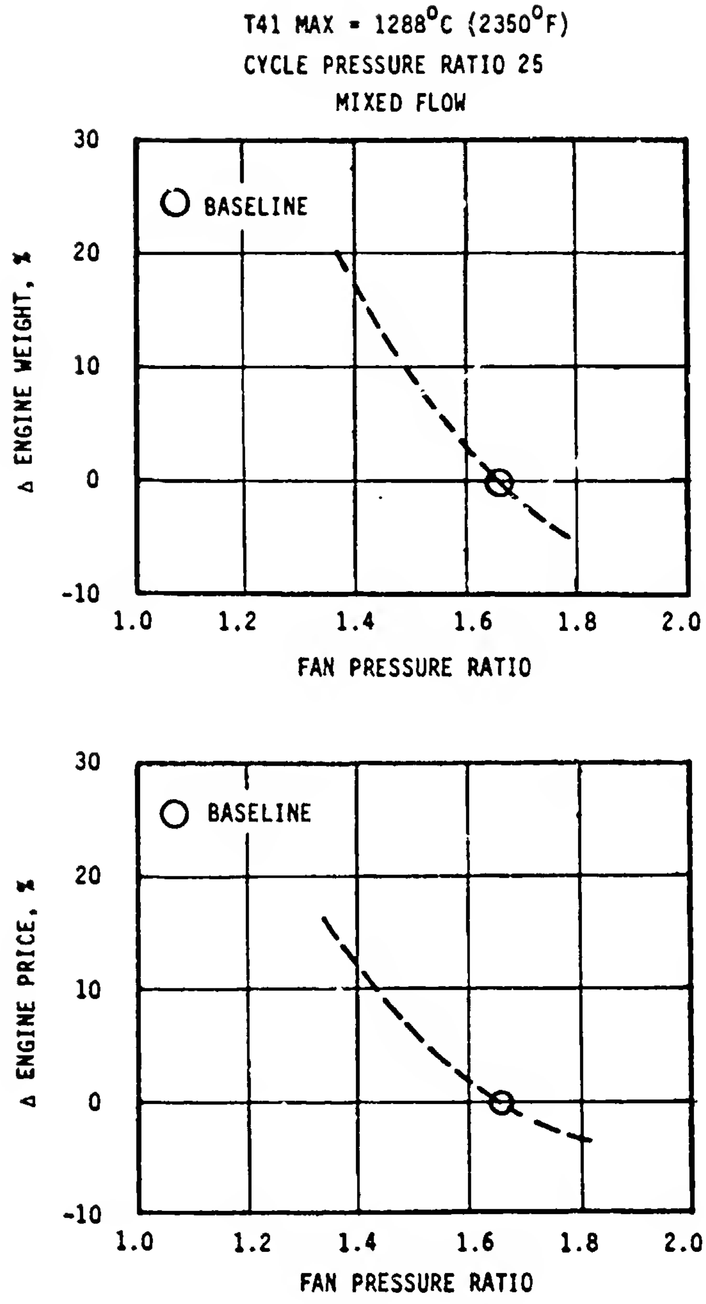

Figure 52. VIGV Engine Fan Pressure Ratio Trends Engine Weight and Engine Price - X-Wing Rotorcraft

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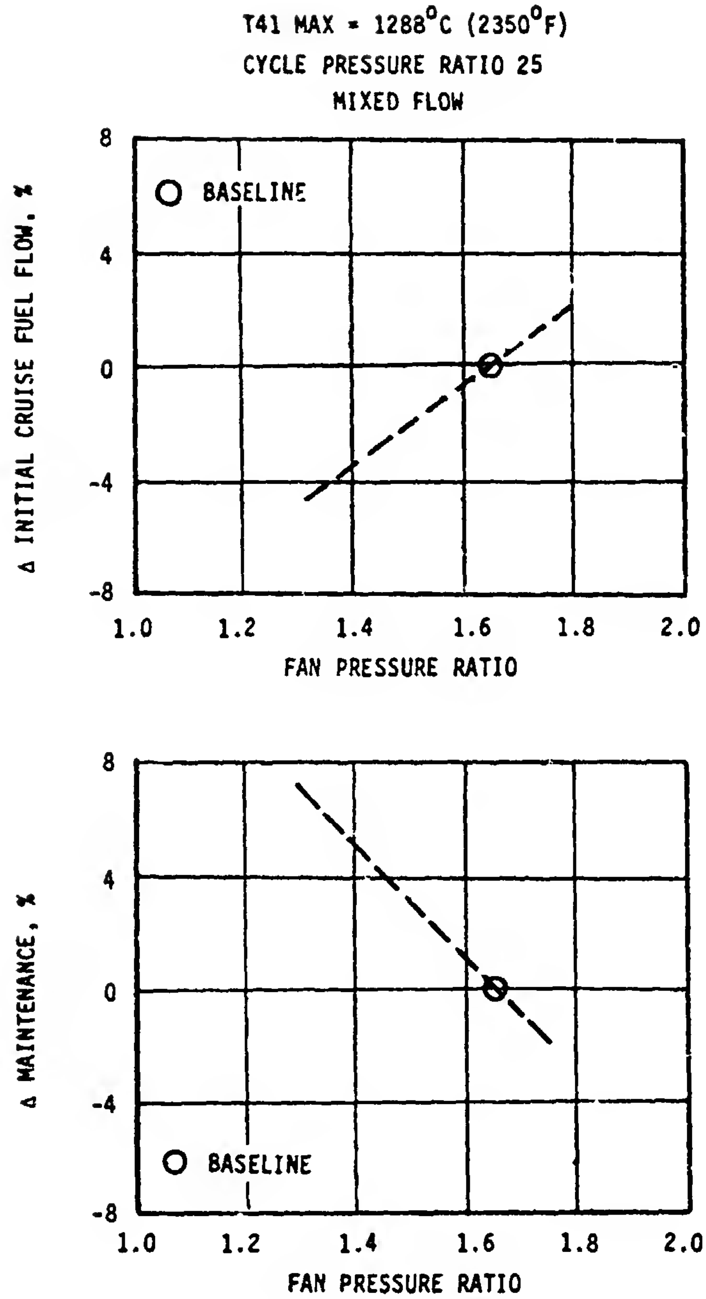

Figure 53. VIGV Engine Pressure Ratio Trends Fuel Flow and Maintenance - X-Wing Rotorcraft

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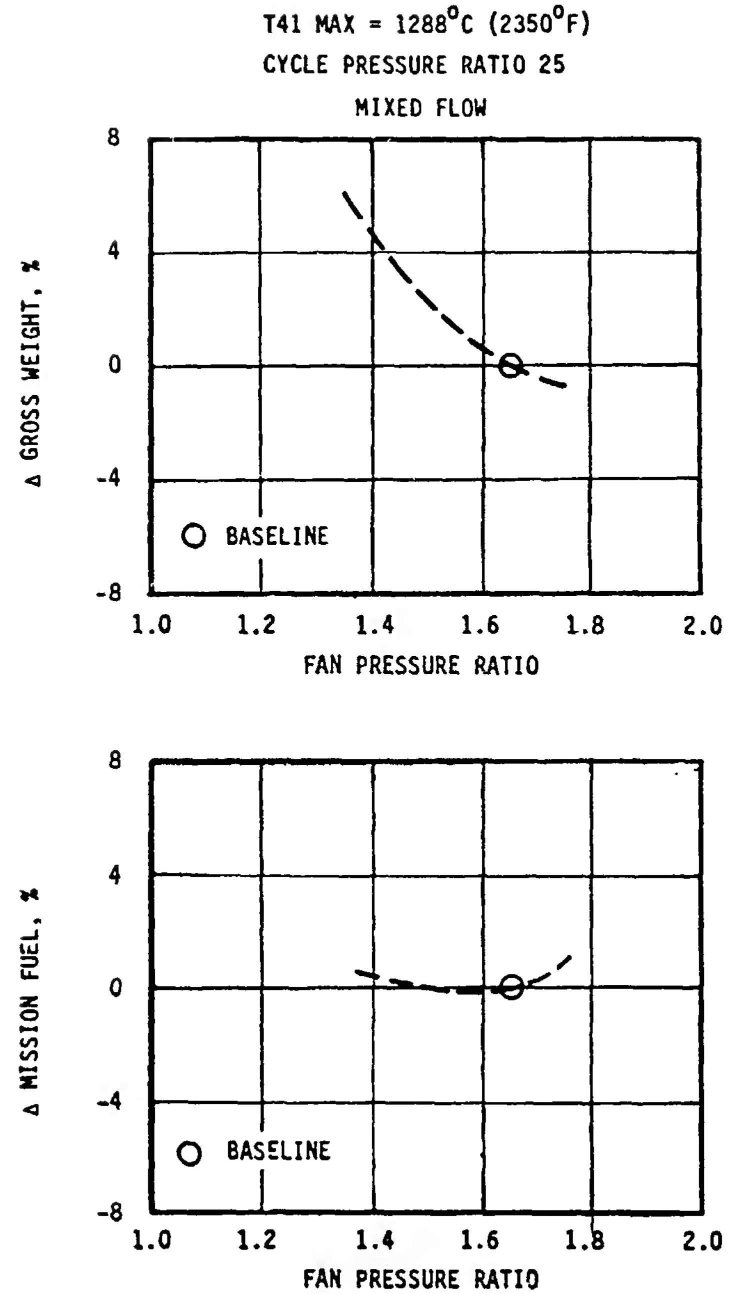

Figure 54. VIGV Engine Pressure Ratio Trends Gross Weight and Mission Fuel - X-Wing Rotorcraft.

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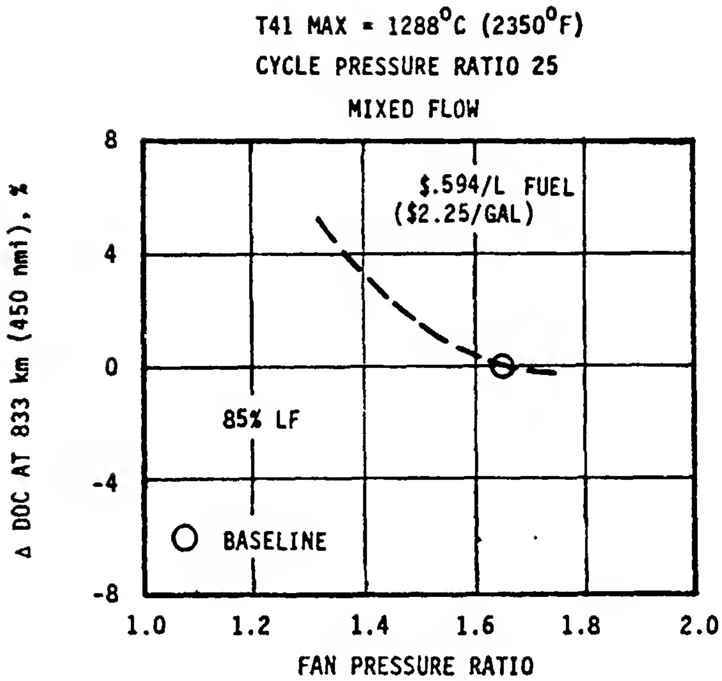


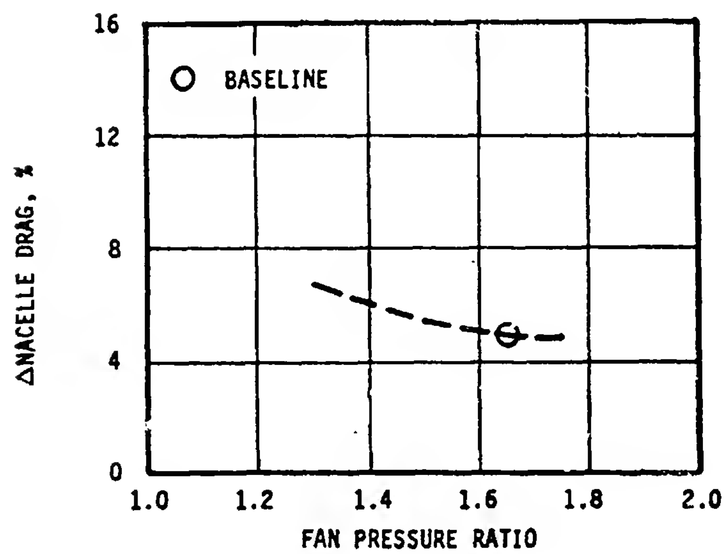


Figure 55. VIGV Engine Pressure Ratio Trends DOC and Nacelle Drag - X-Wing Rotorcraft

FAN PRESSURE RATIO TRENDS - Continued

Separate versus Mixed Exhaust: A separate flow X-Wing engine was defined (see Table 73) with a fan pressure ratio of 1.65, equal to that of the baseline engine. An exhaust velocity ratio (core velocity/fan velocity) of 1.35 was used. The separate flow cycle was markedly inferior relative to the baseline engine (mixed flow) with an 8.0% increase in DOC.

The magnitude of the difference between the separate and mixed flow configurations is greater than exhibited for a conventional turbofan cycle. The reason for this is that the engine sizing is driven by the OEI hover power requirement. If mixed and separate flow designs are sized at the same bypass ratio, then in hover the mixed flow design operates at an effectively larger exhaust area, and therefore lower exhaust pressure ratio, extracting a larger percentage of the available energy as shaft power. Thus, to maintain the same hover capability, the separate flow engine requires a larger core. The larger core has a "feedback" effect also: to provide the same cruise thrust, the core operates lower in T41 and pressure ratio, making for a less efficient cycle. These effects are not present in the conventional turbofan. If the separate flow case is sized at a higher bypass ratio, the core size increase relative to the mixed flow case is smaller, but the fan size increase with bypass ratio is significant. This too has a "feedback" effect: a larger fan has greater windage losses at hover, which again drives up core size, and has greater nacelle drag at cruise.

OVERALL CYCLE PRESSURE RATIO AND T41 TRENDS

Design and Evaluation

The point designs of the ABC and X-Wing VIGV turbofans used for the overall cycle pressure ratio and T41 trends are shown in Tables 74 and 75. For each of the baseline cycles (ABC and X-Wing), two cases with lower cycle pressure ratio and two cases with variations in max T41 from the base were chosen. At the nominal level of T41, compressor stages were removed for the lower cycle pressure ratio cases, holding fan pressure ratio constant. At constant cycle pressure ratio and fan pressure ratio, the effect of T41 variations of ±56°C (100°F) from the baseline value of 1288°C (2350°F) at OEI hover +15°C (27°F) were investigated.

Chargeable cooling flow was varied as a function of turbine inlet temperature (T41) and overall cycle pressure ratio (see Figure 56) to maintain constant blade temperature and life.

The same sizing procedure as in the fan pressure ratio trends was used. Net power at OEI hover and installed thrust at initial cruise were held constant. Note that the nacelle drag is constant for the cycle pressure ratio cases, as the fan pressure ratio and thus the fan flow are not changing.

TABLE 74. ENGINE CONFIGURATIONS FOR CYCLE PRESSURE RATIO AND T41 TREND STUDY - ABC ROTORCRAFT

100% Corrected Fan Speed

Constant Fan Pressure Ratio

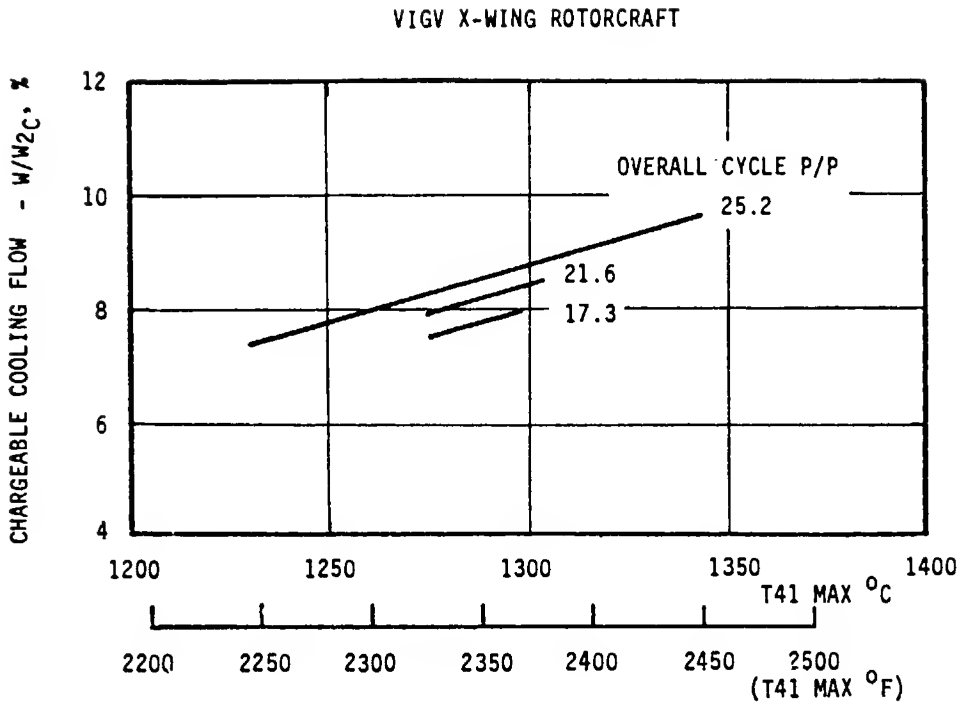
Fan Bypass Pressure Ratio	1.36 →				
Exhaust Type	Sep →				
Geared/Direct Drive	Direct →				
Fan Bypass Ratio	4.4	4.2	4.4	4.0	3.4
Overall Cycle Pressure Ratio	17.1	20.5	25.1	25.1	25.1
No. of Booster Stages	1	1	1	1	1
No. of Compressor Stages	4	5	6	6	6
No. of LPT Stages	5	5	5	5	4
Max T41, °C (°F)	1288 (2350)	1288 (2350)	1343 (2450)	1288 (2350)	1232 (2250)
Δ% Total Corrected Fan Flow	0	0	0	Base	0
Δ% Corrected Core Flow	-10.1	-6.0	-9.2	Base	+11.5

TABLE 75. ENGINE CONFIGURATIONS FOR CYCLE PRESSURE RATIO AND T41 TREND STUDY - X-WING ROTORCRAFT

100% Corrected Fan Speed

Constant Fan Pressure Ratio

Fan Bypass Pressure Ratio	1.65 →				
Exhaust Type	Mixed →				
Geared/Direct Drive	Direct →				
Fan Bypass Ratio	3.1	3.0	3.2	2.9	2.3
Overall Cycle Pressure Ratio	17.3	20.6	25.2	25.2	25.2
No. of Booster Stages	0	0	0	0	0
No. of Compressor Stages	4	5	6	6	6
No. of LPT Stages	3	3	3	3	2
Max T41, °C (°F)	1288 (2350)	1288 (2350)	1343 (2450)	1288 (2350)	1232 (2250)
Δ% Total Corrected Fan Flow	0	0	+2.3	Base	-2.3
Δ% Corrected Core Flow	-9.4	-6.3	-9.5	Base	+5.0



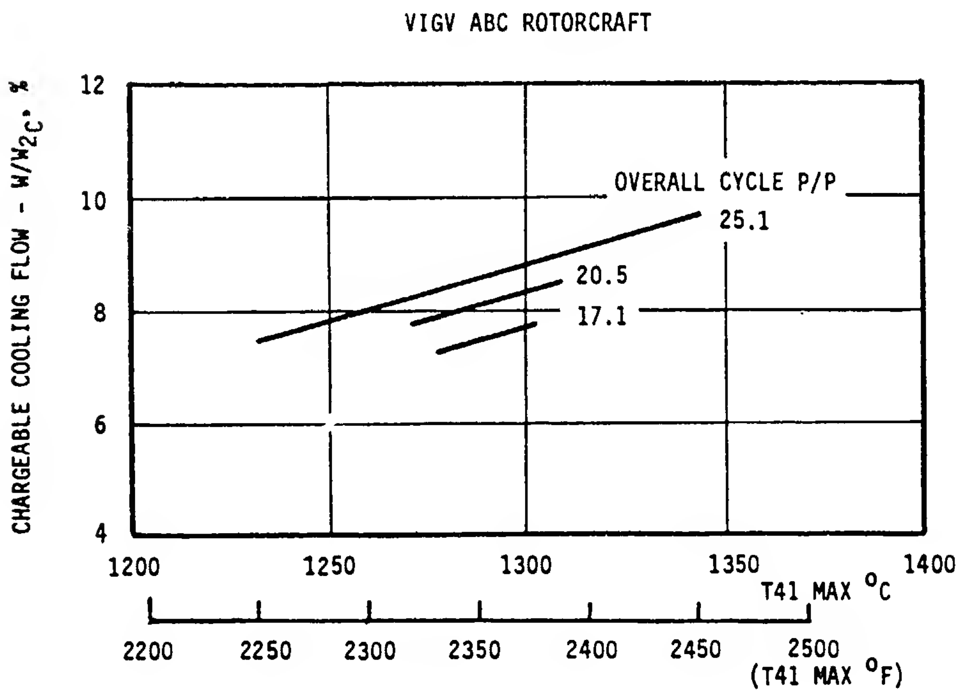


Figure 56. Chargeable Cooling Flow versus T41 Trends

OVERALL CYCLE PRESSURE RATIO AND T41 TRENDS - Continued

ABC Cycle Pressure Ratio and T41 Trends - Discussion of Results

The engine weight trend is shown in Figure 57. The engine weight trend is favorable for rising T41 at constant cycle pressure ratio. The higher cycle pressure ratio engines at constant T41 are penalized due to the reduced specific output (power/airflow). The additional compressor stages for the higher cycle pressure ratio cases are also detrimental to the weight trend. As with the fan pressure ratio study, the engine price trend follows the engine weight trend.

Although the hot section will be costlier for increasing T41, this trend is offset by the reduction in necessary core size for the higher T41 cases. The engine price and maintenance trends increase with rising cycle pressure ratio, showing that the core weight dominates. (As with the fan pressure ratio trends, the core also has the dominent effect on engine maintenance).

Increasing T41 or raising overall cycle pressure ratio is favorable toward the initial cruise fuel flow, as shown in Figure 58.

Figure 59 indicates that the gross weight and mission fuel trends follow those for the engine weight and initial cruise fuel flow, respectively. From Figure 60, the minimum DOC occurs at a cycle pressure ratio below that of the baseline case. The improvement at a cycle pressure ratio of 17.3 is 1.1% DOC over the base engine.

Increasing T41 leads to an improvement in initial cruise fuel flow, engine weight, price and maintenance. Therefore, increasing T41 by +56°C (+100°F) from the baseline value of 1288°C (2350°F) at OEI hover results in an improvement of 2.4% in DOC.

X-Wing Cycle Pressure Ratio and T41 Trends

Figures 61 and 62 show that the X-Wing cycle pressure ratio and T41 trends are similar to the corresponding ABC turbofans. Lower cycle pressure ratio and increased T41 results in the reduction of engine weight, price, and maintenence as displayed in Figures 61 and 62. Initial cruise fuel flow is higher for the engines with lower cycle pressure ratio.

The gross weight and mission fuel trends exhibited in Figure 63 show the result of the influence of engine weight and initial cruise fuel flow, as with the ABC turbofans. Mission fuel reaches a minimum near a cycle pressure ratio of 22 (due to the conflicting effects of engine weight and initial cruise fuel flow).

Nacelle drag (Figure 64) is constant because fan pressure ratio and airflow are invariant. DOC reaches a minimum near a cycle pressure ratio of 21 and represents a gain of 1.3% DOC over the baseline.

This comparison was repeated using the refined Task V sizing procedure (see "Mission Analysis Refinements", page 143) for the same core pressure ratios (corresponding cycle pressure ratios are higher for the Task V sizing procedure). The DOC results were dependent on the sizing procedure used. The trend using the Task V sizing procedure was similar to the Task IV result, but the minimum DOC occurs at a higher cycle pressure ratio for the Task V sizing procedure. The gain in reducing the core pressure ratio from 22 to 18 is only 0.3% using the Task V procedure. Since the Task V sizing procedure resulted in better convertible engines, the conclusions on best cycle pressure using that method was given more weight.

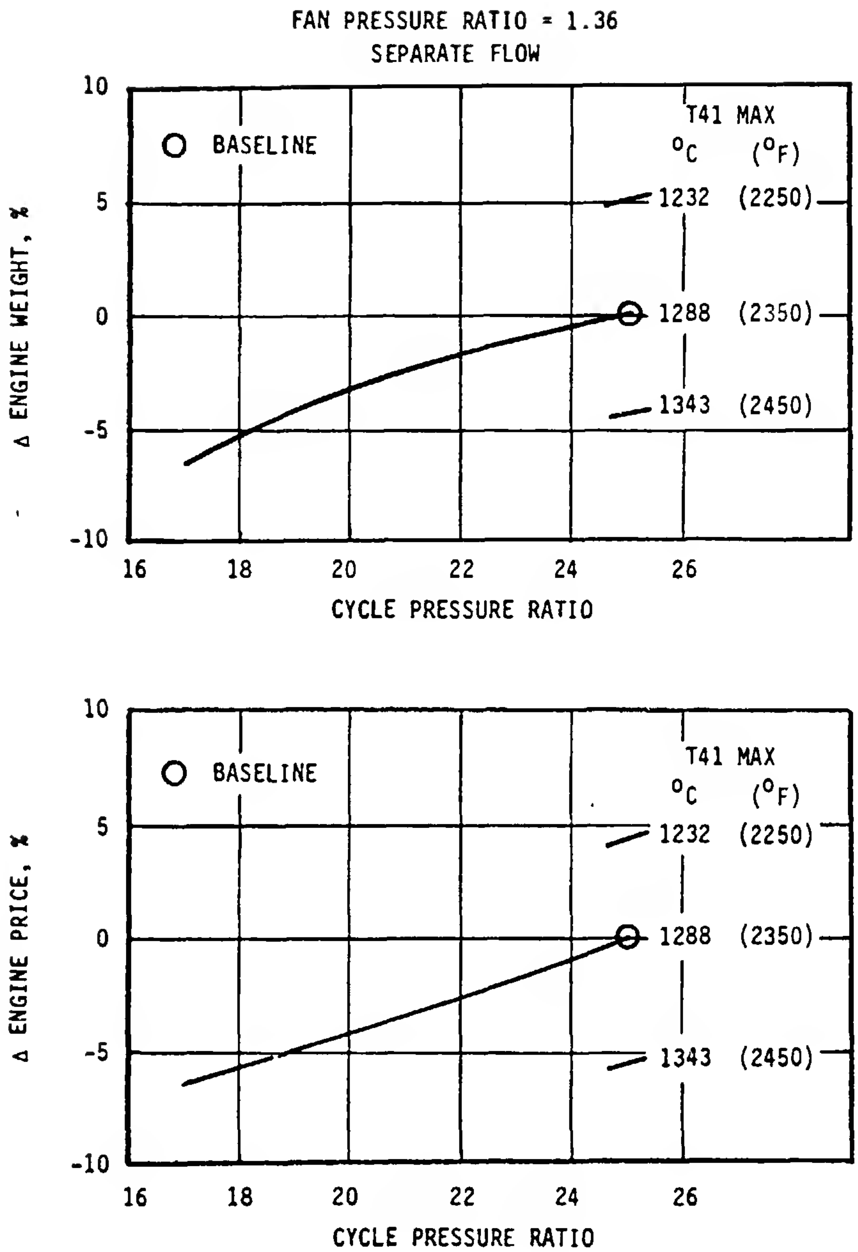


Figure 57. VIGV Cycle Pressure Ratio and T41 Trends Engine Weight and Engine Price - ABC Rotorcraft

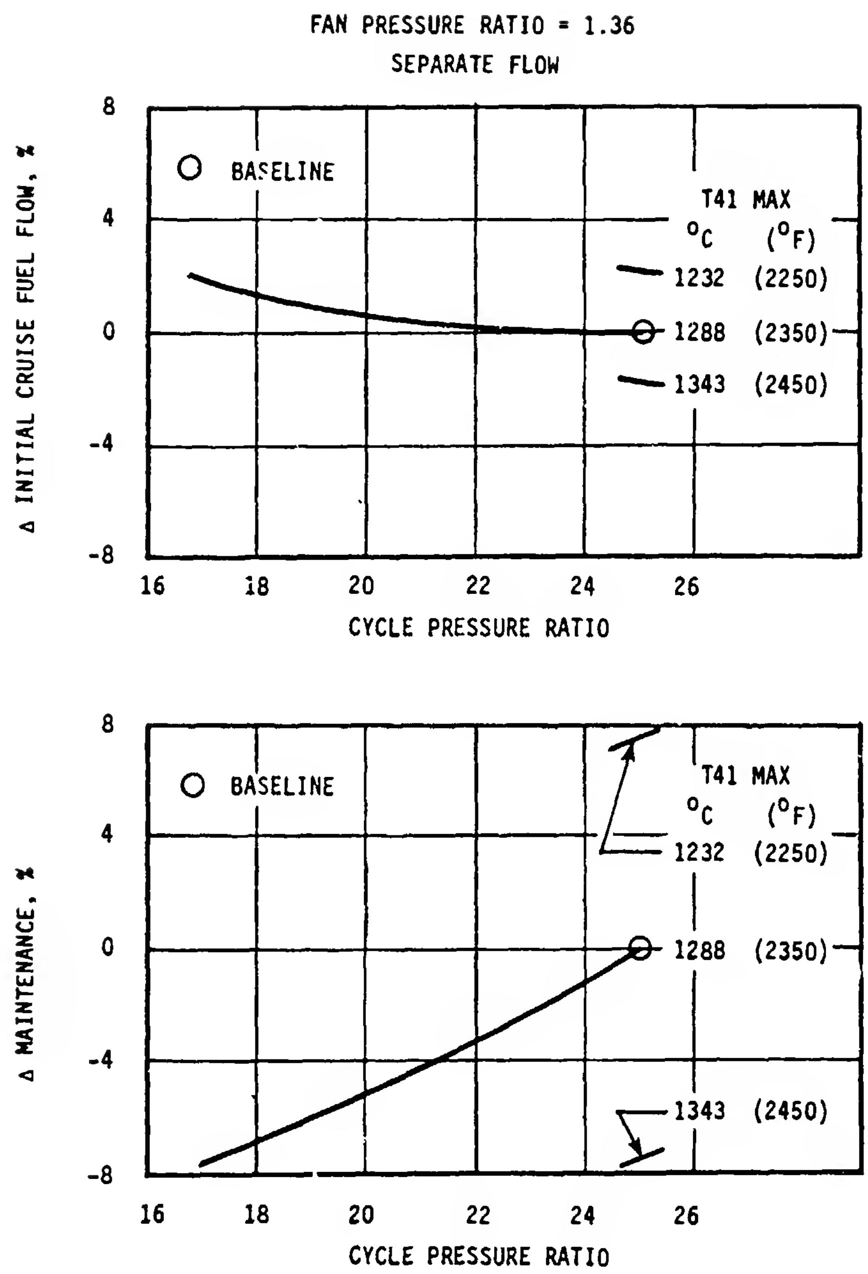


Figure 58. VIGV Cycle Pressure Ratio and T41 Trends Fuel Flow and Maintenance - ABC Rotorcraft

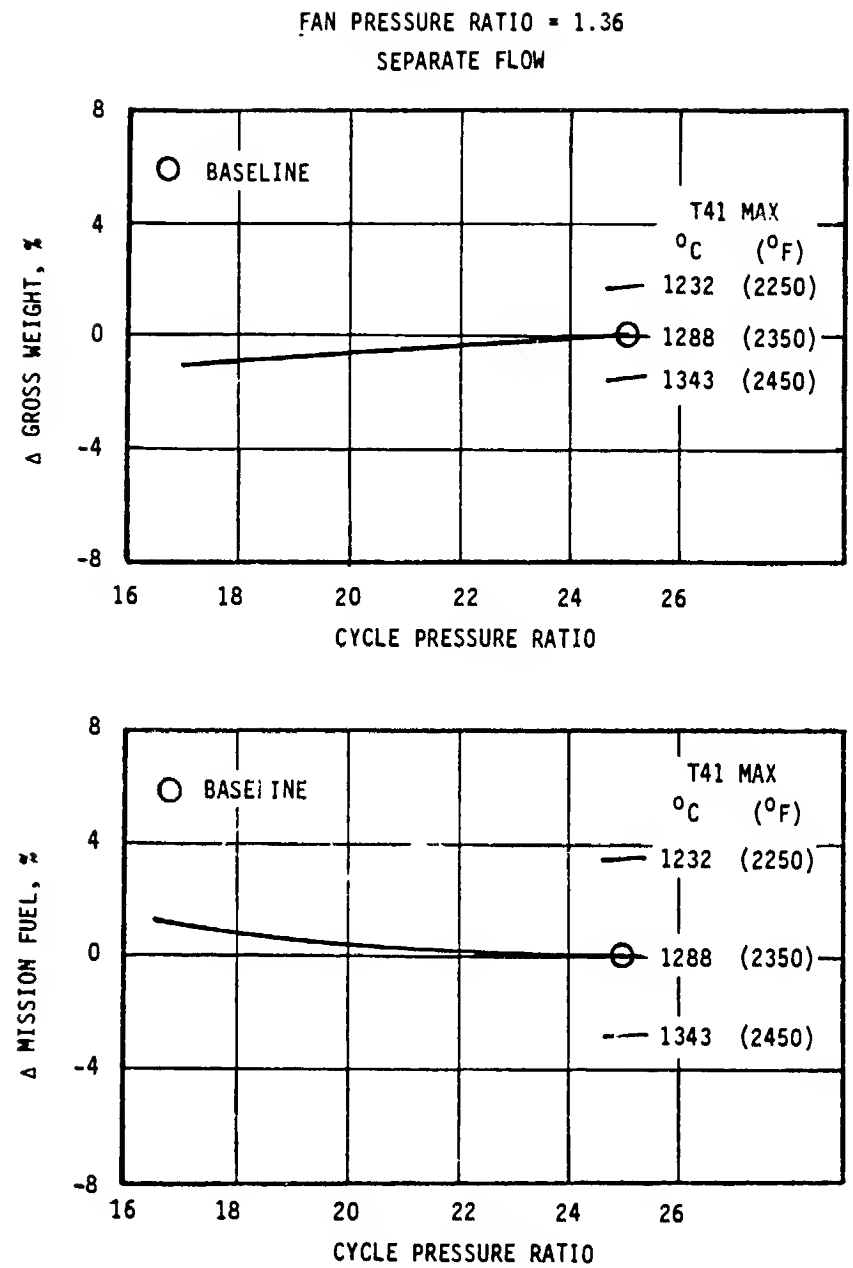


Figure 59. VIGV Cycle Pressure Ratio and T41 Trends Gross Weight and Mission Fuel - ABC Rotorcraft

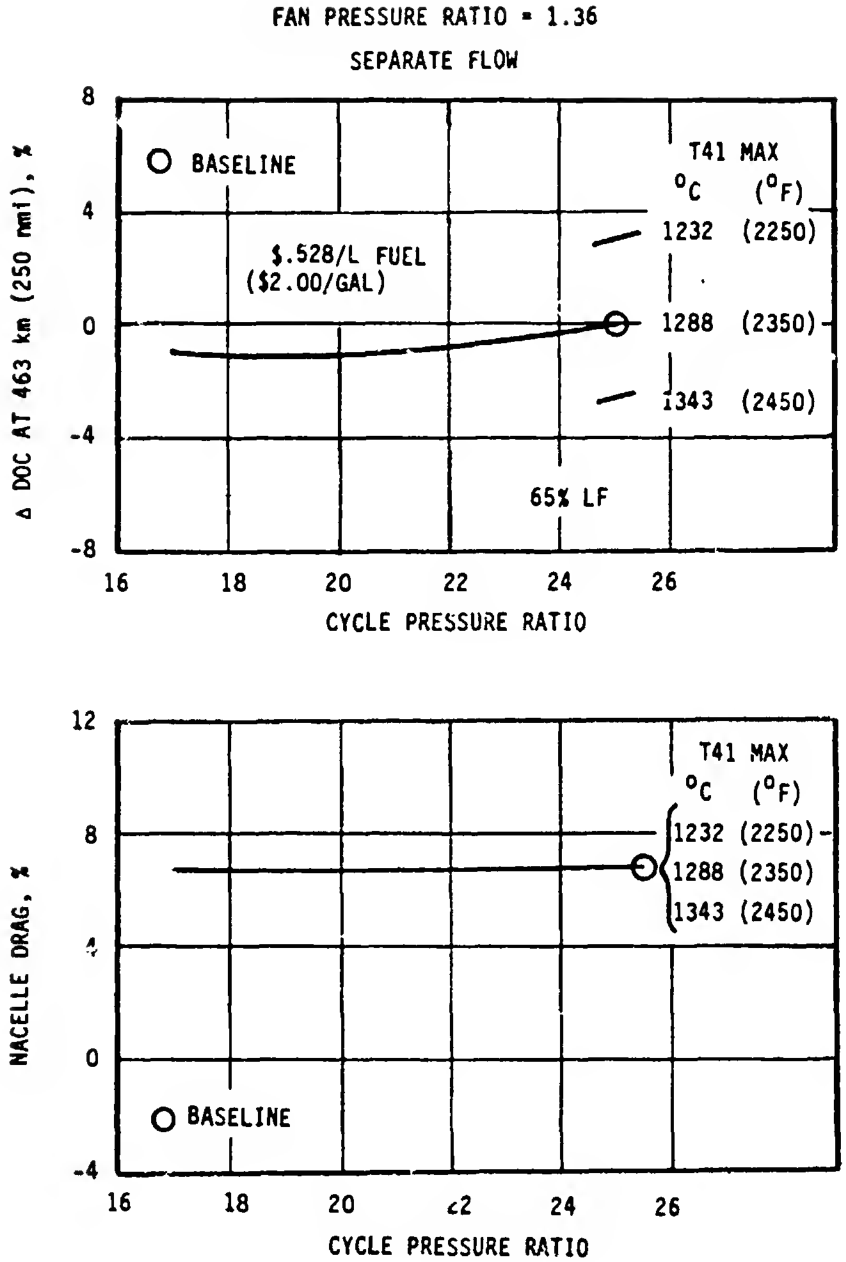
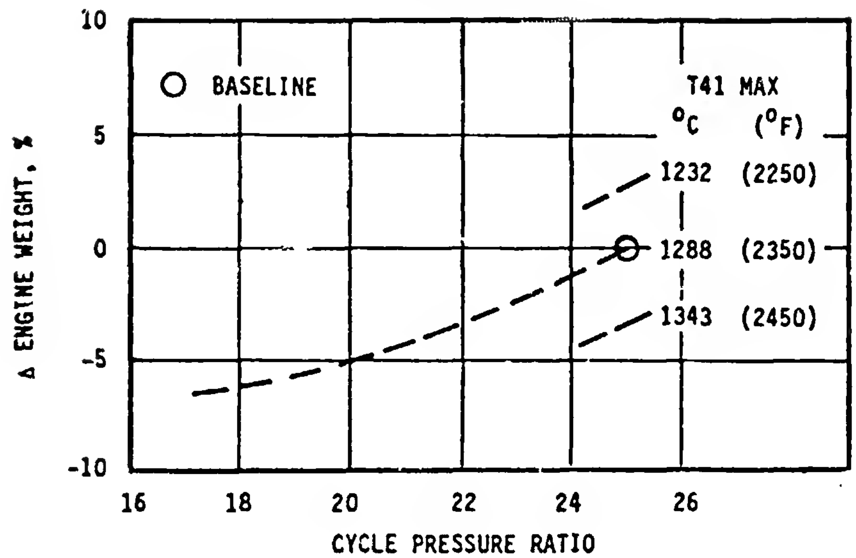


Figure 60. VIGV Cycle Pressure Ratio and T41 Trends DOC and Nacelle Drag - ABC Rotorcraft

FAN PRESSURE RATIO = 1.65
MIXED FLOW



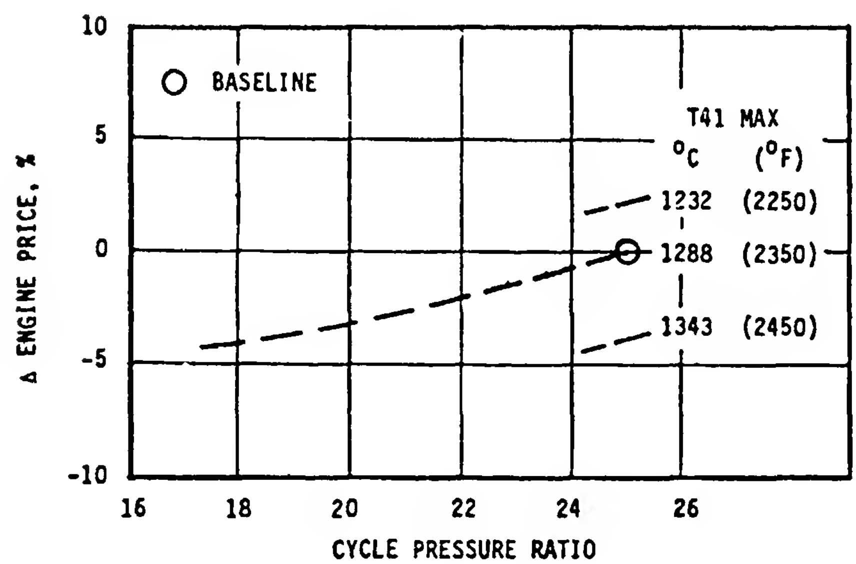


Figure 61. VIGV Cycle Pressure Ratio and T41 Trends Engine Weight and Engine Price - X-Wing Rotorcraft

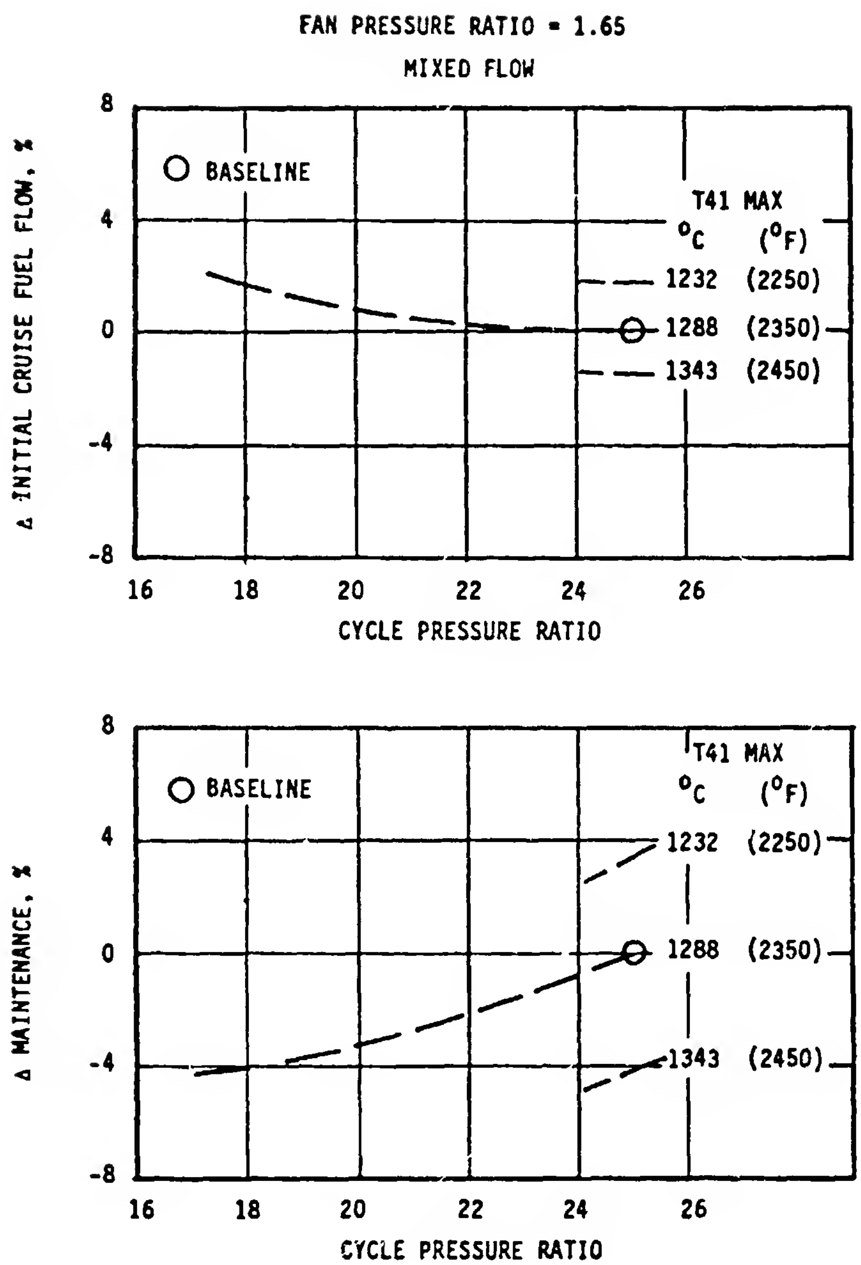


Figure 62. VIGV Cycle Pressure Ratio and T41 Trends Fuel Flow and Maintenance - X-Wing Rotorcraft

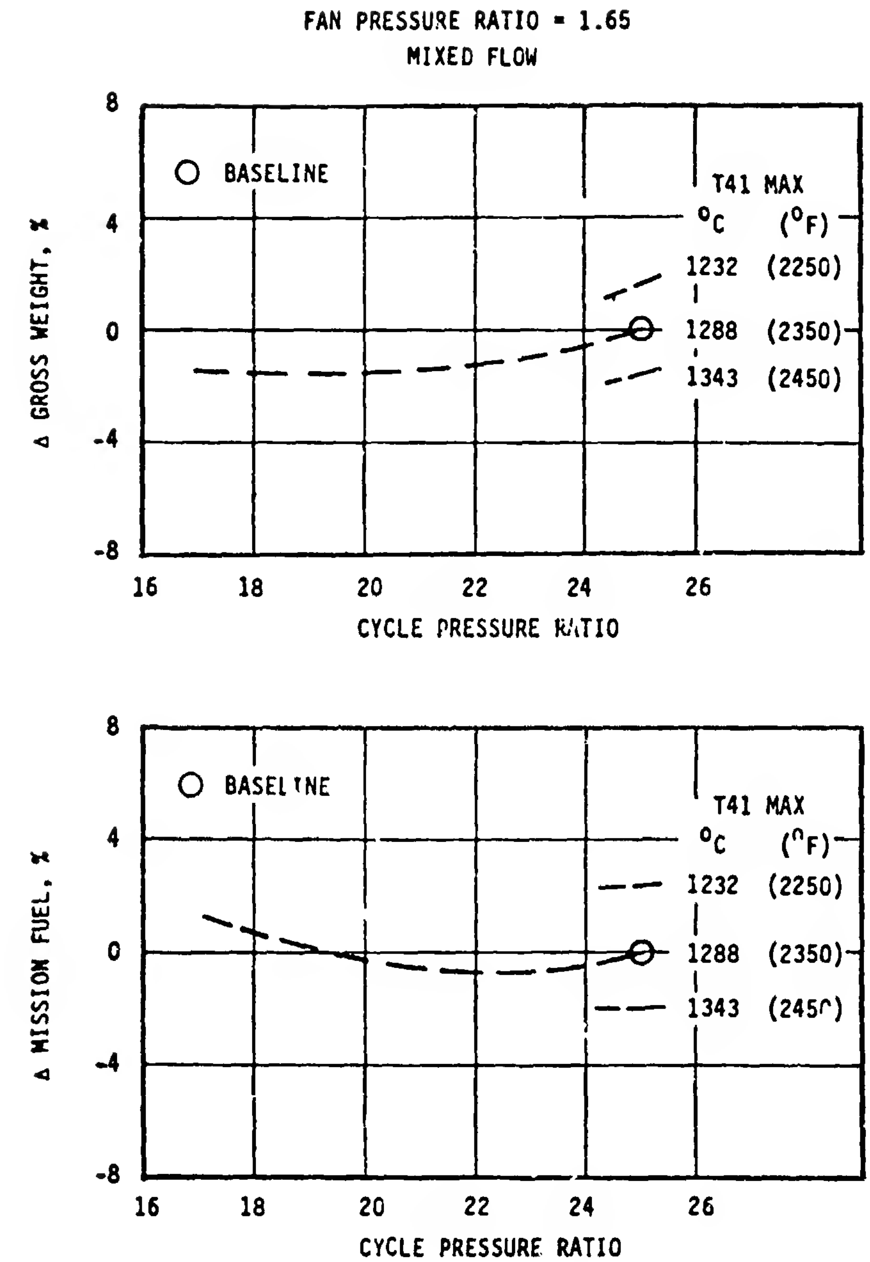
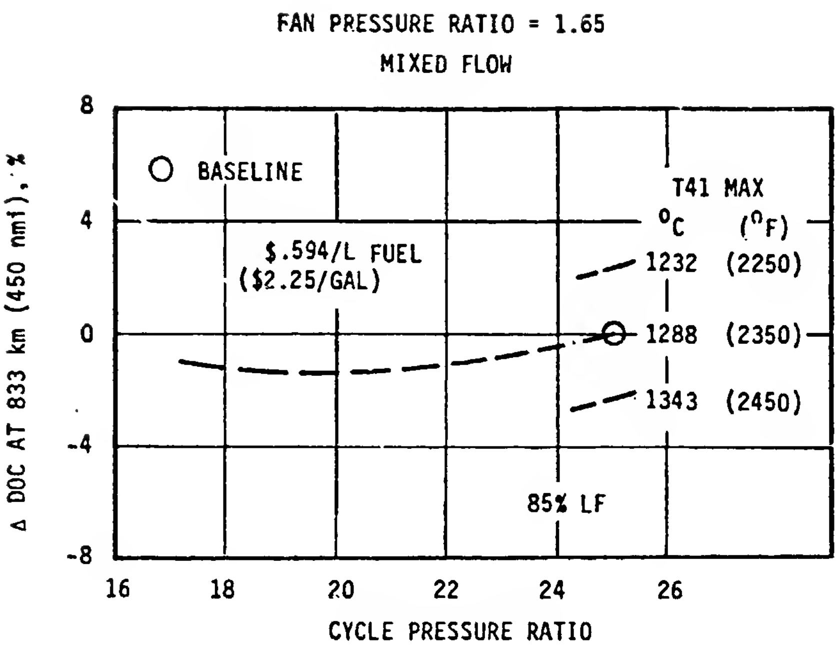


Figure 63. VIGV Cycle Pressure Ratio and T41 Trends Gross Weight and Mission Fuel - X-Wing Rotorcraft



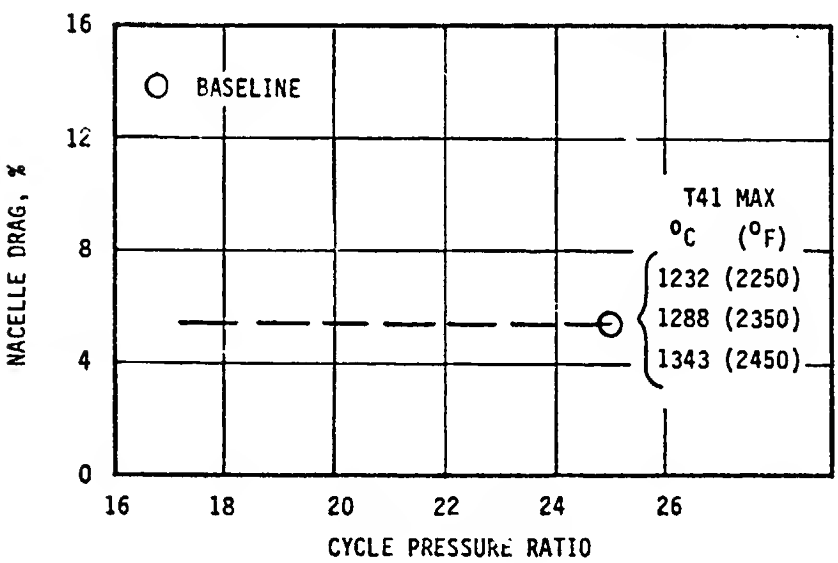


Figure 64. VIGV Cycle Pressure Ratio and T41 Trends DOC and Nacelle Drag - X-Wing Rotorcraft

TASK V

DEFINITION OF PREFERRED POWERPLANTS

TASK V - DEFINITION OF PREFERRED POWERPLANTS

MISSION ANALYSIS REFINEMENTS

The baseline powerplants for both Tasks I and II were selected based on prior General Electric experience. Many design choices had to be made without a complete understanding of their impact on the aircraft mission and economic results. As the study progressed, it was found that some of the conventional wisdom applied to sizing the baseline engines was not applicable to these unconventional aircraft, and a procedure began to emerge for tailoring engine designs to their unique requirements.

To keep the comparisons among engine types equitable, refined versions of the Task I and II baseline engines and the Task III prop/shaft engines were defined. The primary departures from the original designs were in the areas of fan design and provision for OEI operation. In addition, the opportunity was taken to analyze engine and transmission weight and pricing in greater detail than for Tasks I, II, and III, and to review all component performance levels.

The impact of the powerplant refinements on mission parameters (gross weight, DOC, etc.) was assessed by using the sensitivities derived in Task II and III. These sensitivities are collected and summarized in Tables 76 and 77 for the ABC vehicle, and Tables 78 and 79 for the X-Wing.

TABLE 76. MISSION MERIT FACTOR SENSITIVITIES
CONVERTIBLE ENGINES

ABC Rotorcraft - 370 km (200 nmi) Mission

16580 kg (36550 lbm) Gross Weight - $.528/l ($2.00/gal) Fuel

1981 Economy

Parameter	Change	% Change in Gross Weight	% Change in Acquisition Cost	% Change in Block Fuel	% Change in DOC
SFC	1%	.26	.14	1.2	.57
Engine Weight	1%	.22	.17	.18	.14
	45.4 kg/Engine (100 lbm)	1.4	1.1	1.2	.9
Transmission Wt.	1%	.15	.16	.12	.12
	90.7 kg/Aircraft (200 lbm)	1.0	1.0	.8	.8
Engine Price	1%	-	.29	-	.08
	$10,000/Engine		.19		.05
Engine Maintenance	1%	-	-	-	.09
	$1.00/Engine·hr				.17

TABLE 77. MISSION MERIT FACTOR SENSITIVITIES
PROP/SHAFT ENGINES

ABC Rotorcraft - 370 km (200 nmi) Mission

16190 kg (35690 lbm) Gross Weight - $.528/l ($2.00/gal) Fuel

1981 Economy

Parameter	Change	% Change in Gross Weight	Acquisition Cost	Block Fuel	DOC
SFC	1%	.23	.16	1.2	.61
Engine Weight	1%	.15	.15	.13	.12
	45.4 kg/Engine (100 lbm)	1.3	1.3	1.1	1.1
Transmission Wt.	1%	.16	.20	.13	.16
	90.7 kg/Aircraft (200 lbm)	.9	1.1	.7	.9
Engine Price	1%	-	.26	-	.07
	$10,000/Engine		.28		.08
Engine Maintenance	1%	-	-	-	.08
	$1.00/Engine·hr				.19

TABLE 78. MISSION MERIT FACTOR SENSITIVITIES
CONVERTIBLE ENGINES

X-Wing Rotorcraft - 833 km (450 nmi) Mission

21645 kg (47720 lbm) Gross Weight - $.594/l ($2.25/gal) Fuel

1981 Economy

Parameter	Change	% Change in Gross Weight	Acquisition Cost	Block Fuel	DOC
SFC	1%	.33	.22	1.2	.65
Engine Weight	1%	.34	.26	.25	.24
	45.4 kg/Engine (100 lbm)	1.3	1.0	.95	.9
Transmission Wt.	1%	.24	.26	.18	.21
	90.7 kg/Aircraft (200 lbm)	1.0	1.1	.8	.9
Engine Price	1%	-	.31	-	.10
	$10,000/Engine		.14		.04
Engine Maintenance	1%	-	-	-	.08
	$1.00/Engine·hr				.11

TABLE 79. MISSION MERIT FACTOR SENSITIVITIES
PROP/SHAFT ENGINES

X-Wing Rotorcraft - 833 km (450 nmi) Mission

23740 kg (52340 lbm) Gross Weight - $.594/l ($2.25/gal) Fuel

1981 Economy

Parameter	Change	% Change in Gross Weight	Acquisition Cost	Block Fuel	DOC
SFC	1%	.30	.24	1.2	.62
Engine Weight	1%	.27	.28	.22	.23
	45.4 kg/Engine (100 lbm)	1.1	1.1	.9	.95
Transmission Wt.	1%	.39	.47	.30	.38
	90.7 kg/Aircraft (200 lbm)	1.0	1.2	.8	1.0
Engine Price	1%	-	.29	-	.10
	$10,000/Engine		.17		.06
Engine Maintenance	1%	-	-	-	.07
	$1.00/Engine·hr				.12

TASK V - DEFINITION OF PREFERRED POWERPLANTS - Continued

MISSION ANALYSIS REFINEMENTS - Continued

Refined Convertible VIGV Engines

The cycle selection studies of Task IV confirmed the selection of the baseline engine fan pressure ratio for both the ABC and X-Wing as being near optimum for minimum DOC. Therefore no changes were made in this parameter in Task V in defining the refined convertible VIGV engines. Although decreasing cycle pressure ratio showed a small advantage, no change was made in this parameter on the basis that the gain was small.

The requirement to provide one engine inoperative hover capability was, as mentioned previously. the determining factor in sizing the separate turboshaft, prop/shaft, and convertible engines. These engines are thus oversized for the cruise requirement, and must operate inefficiently, at low part power, in cruise. The initial engine designs were done for a moderate turbine inlet temperature of 1288°C (2350°F) at OEI, and with compressor rotational speed limited to 106%. Task IV showed a payoff for increased T41, as expected, and a study was carried out to determine the maximum T41 that was acceptable for OEI operation with no impact on the turbine cooling design.

The selected maximum T41 of 1371°C (2500°F) allows the engines to be safely operated at the OEI condition. However, life of the HPT blades is used up at 11 times the normal rate, i.e. for each 5 min. at OEI, life of the blades is decreased by 0.2%. To qualify this OEI rating per FAA requirement, the engines would be subjected to a 150 h endurance test which includes 2:05 h at OEI. The calculated life is adequate to qualify the engine, and provide over 5000 h mission life, assuming 1/2% of mission time is at OEI.

MISSION ANALYSIS REFINEMENTS - Continued

The core engines for the three engine types (separate turboshaft, prop/shaft and VIGV convertible) were then all re-sized to operate at 1371°C (2500°F) T41 and at the compressor aerodynamic design point for the sea level, ISA +15°C (27°F), OEI hover condition. No arbitrary limitation was imposed on core rotational speed; it was a consequence of operating the compressor at its aerodynamic design condition. Any change in maximum compressor speed from the baseline engines was accounted for in the component weight calculations.

The baseline Task II VIGV fan designs were conventional in the sense that the aerodynamic design points of the fan hub and fan tip were at the same condition, that is, at design cruise. Fan hub performance is more important, however, at the OEI hover condition which sizes the core. Therefore, for the refined VIGV engine, the following sizing procedure was adopted, with fan hub and tip aerodynamic designs at different conditions.

1. Fan tip speed at cruise was selected to give good cruise performance for the desired pressure ratio. This is the fan tip aerodynamic design point, with inlet and exit guide vanes full open.

2. Fan hub wheel speed at OEI is a function of cruise tip speed, output speed scheduling, and fan blade geometry.

3. The fan hub was designed for good performance at the available hub wheel speed at OEI. This is the fan hub aerodynamic design point.

4. The core compressor was also sized to operate at its aerodynamic design point at OEI.

A family of fan blades was designed for varying hub and tip pressure ratios for Task IV, and designs selected from that family for the refined VIGV engine. Tables 80 and 81 compare the Task II and the refined fan blade designs of the ABC and X-Wing, respectively. The ABC engine required a 5 stage fan drive/power turbine (same as Task II), and the X-Wing a 4 stage design (increase of one stage from Task II).

The net effect of the increased OEI temperature rating and the re-designed fan was to reduce core engine size substantially (23% for the ABC and 30% for the X-Wing) and to increase T41, cycle pressure ratio, and bypass ratio at cruise, all of which reduce cruise SFC. Tables 82 and 83 compare the Task II and refined engines, scaled to the same OEI power.

TABLE 80A. FAN BLADE COMPARISON - ABC

SI Units

	Task II VIGV Convertible	Task V VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, m/s	317	308
Corrected Hub Speed, $UH/\sqrt{\theta}$, m/s	184	143
Overall Radius Ratio, r_H/r_T	.58	.40
Bypass Ratio	3.8	4.6
Tip Pressure Ratio	1.36	1.36
Hub Pressure Ratio	1.37	1.28
Tip Specific Flow, $W\sqrt{\theta}/\delta A$, kg/s·m^2	205	186
Hub Specific Flow, $W\sqrt{\theta}/\delta A$, kg/s·m^2	147	156
Overall Specific Flow, $W\sqrt{\theta}/\delta A$, kg/s·m^2	181	173
Tip Efficiency	.870	.896
Hub Efficiency	.832	.900

TABLE 80B. FAN BLADE COMPARISON - ABC

English Units	Task II VIGV Convertible	Task V VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, ft/sec	1040	1010
Corrected Hub Speed, $UH/\sqrt{\theta}$, ft/sec	603	470
Overall Radius Ratio, r_H/r_T	.58	.40
Bypass Ratio	3.8	4.6
Tip Pressure Ratio	1.36	1.36
Hub Pressure Ratio	1.37	1.28
Tip Specific Flow, $W\sqrt{\theta}/\delta A$, lbm/sec·ft^2	42.0	38.0
Hub Specific Flow, $W\sqrt{\theta}/\delta A$, lbm/sec·ft^2	30.2	32.0
Overall Specific Flow, $W\sqrt{\theta}/\delta A$, lbm/sec·ft^2	37.1	35.5
Tip Efficiency	.870	.896
Hub Efficiency	.832	.900

TABLE 81A. FAN BLADE COMPARISON - X-WING

SI Units	Task II VIGV Convertible	Task V VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, m/s	421	396
Corrected Hub Speed, $UH/\sqrt{\theta}$, m/s	192	168
Overall Radius Ratio, r_H/r_T	.45	.45
Bypass Ratio	2.8	3.9
Tip Pressure Ratio	1.65	1.65
Hub Pressure Ratio	1.47	1.42
Tip Specific Flow, $W\sqrt{\theta}/\delta A$, kg/s·m^2	203	186
Hub Specific Flow, $W\sqrt{\theta}/\delta A$, kg/s·m^2	157	156
Overall Specific Flow, $W\sqrt{\theta}/\delta A$, kg/s·m^2	183	174
Tip Efficiency	.868	.883
Hub Efficiency	.835	.905

TABLE 81B. FAN BLADE COMPARISON - X-WING

English Units	Task II VIGV Convertible	Task V VIGV Convertible
Corrected Tip Speed, $UT/\sqrt{\theta}$, ft/sec	1380	1300
Corrected Hub Speed, $UH/\sqrt{\theta}$, ft/sec	630	550
Overall Radius Ratio, r_H/r_T	.45	.45
Bypass Ratio	2.8	3.9
Tip Pressure Ratio	1.65	1.65
Hub Pressure Ratio	1.47	1.42
Tip Specific Flow, $W\sqrt{\theta}/\delta A$, lbm/sec·ft^2	41.5	38.0
Hub Specific Flow, $W\sqrt{\theta}/\delta A$, lbm/sec·ft^2	32.2	32.0
Overall Specific Flow, $W\sqrt{\theta}/\delta A$, lbm/sec·ft^2	37.5	35.6
Tip Efficiency	.868	.883
Hub Efficiency	.885	.905

TABLE 82A. COMPARISON OF TASK II AND REFINED TASK V VIGV ENGINES
ABC ROTORCRAFT - CONSTANT OEI POWER

SI Units

	Task II Baseline Engine	Task V Refined Engine	Difference
OEI Rated T41, °C	1288	1371	+83°
OEI Output Power, kW	3885	3885	0
Maximum Core Speed, %	106	106.7	+0.7%
Design Cruise Power, kW	1335	1335	0
Design Cruise Thrust, N	7985	7985	0
Design Cruise T41, °C	1120	1205	+85°
100% Core $W\sqrt{\theta}/\delta$, kg/s	15.6	12.0	-23%
100% Fan Tip $W\sqrt{\theta}/\delta$, kg/s	69.4	65.8	-8.4%
100% Fan Hub $W\sqrt{\theta}/\delta$, kg/s	18.2	14.4	
Design Cruise BPR	3.9	5.1	
100% Core Pressure Ratio	22	22	
100% Fan Tip Pressure Ratio	1.36	1.36	
100% Fan Hub Pressure Ratio	1.37	1.28	
Overall Pressure Ratio, OEI	25.6	27.5	+7.4%
Overall Pressure Ratio, Cruise	22.3	24.1	+8.1%
Δ SFC, Mission Weighted, %	Base	-9.8	
Engine Weight*, kg	703	583	-17%
Engine Price*, $ x 10^{-3}	1530	1175	-23%
Engine Maintenance*, $/Engine·hr	54.00	45.20	-16%

*Not including PTO

TABLE 82B. COMPARISON OF TASK II AND REFINED TASK V VIGV ABC ROTORCRAFT - CONSTANT OEI POWER

English Units

	Task II Baseline Engine	Task V Refined Engine	Difference
OEI Rated T41, °F	2350	2500	+150°
OEI Output Power, hp	5210	5210	0
Maximum Core Speed, %	106	106.7	+0.7%
Design Cruise Power, hp	1790	1790	0
Design Cruise Thrust, lb	1795	1795	0
Design Cruise T41, °F	2045	2200	+155°
100% Core $W\sqrt{\theta}/\delta$, lbm/sec	34.4	26.4	-23%
100% Fan Tip $W\sqrt{\theta}/\delta$, lbm/sec	153	145	-8.4%
100% Fan Hub $W\sqrt{\theta}/\delta$, lbm/sec	40.1	31.8	
Design Cruise BPR	3.9	5.1	
100% Core Pressure Ratio	22	22	
100% Fan Tip Pressure Ratio	1.36	1.36	
100% Fan Hub Pressure Ratio	1.37	1.28	
Overall Pressure Ratio, OEI	25.6	27.5	+7.4%
Overall Pressure Ratio, Cruise	22.3	24.1	+8.1%
Δ SFC, Mission Weighted, %	Base	-9.8	
Engine Weight*, lbm	1550	1285	-17%
Engine Price*, \$ x 10^{-3}	1530	1175	-23%
Engine Maintenance*, \$/Engine·hr	54.00	45.20	-16%

*Not including PTO

TABLE 83A. COMPARISON OF TASK II AND REFINED TASK V VIGV ENGINES X-WING ROTORCRAFT - CONSTANT OEI POWER

SI Units

	Task II Baseline Engine	Task V Refined Engine	Difference
OEI Rated T41, °C	1288	1371	+83°
OEI Output Power, kW	8055	8055	0
Maximum Core Speed, %	106	108.4	+2.4%
Design Cruise Power, kW	250	250	0
Design Cruise Thrust, N	11475	11475	0
Design Cruise T41, °C	1015	1125	+110°
100% Core, $W\sqrt{\theta}/\delta$, kg/s	32.8	23.0	-29.8%
100% Fan Tip $W\sqrt{\theta}/\delta$, kg/s	117.5	118.8	-6.7%
100% Fan Hub $W\sqrt{\theta}/\delta$, kg/s	42.5	30.4	
Design Cruise BPR	2.7	3.7	
100% Core Pressure Ratio	22	22	
100% Fan Tip Pressure Ratio	1.65	1.65	
100% Fan Hub Pressure Ratio	1.47	1.42	
Overall Pressure Ratio, OEI	26.5	30.6	+15.5%
Overall Pressure Ratio, Cruise	24.1	28.9	+19.9%
ΔSFC, Mission Weighted, %	Base	-8.5	
Engine Weight*, kg	1190	1052	-12%
Engine Price*, \$ x 10^{-3}	2220	1800	-19%
Engine Maintenance*, \$/Engine·hr	66.70	50.20	-25%

*Not including PTO

TABLE 83B. COMPARISON OF TASK II AND REFINED TASK V VIGV ENGINES
X-WING ROTORCRAFT - CONSTANT OEI POWER

English Units

	Task II Baseline Engine	Task V Refined Engine	Difference
OEI Rated T41, °F	2350	2500	+150°
OEI Output Power, hp	10800	10800	0
Maximum Core Speed, %	106	108.4	+2.4%
Design Cruise Power, hp	335	335	0
Design Cruise Thrust, lb	2580	2580	0
Design Cruise T41, °F	1855	2055	+200°
100% Core, $W\sqrt{\theta}/\delta$, lbm/sec	72.4	50.8	-29.8%
100% Fan Tip $W\sqrt{\theta}/\delta$, lbm/sec	259	262	-6.7%
100% Fan Hub $W\sqrt{\theta}/\delta$, lbm/sec	93.8	67.0	
Design Cruise BPR	2.7	3.7	
100% Core Pressure Ratio	22	22	
100% Fan Tip Pressure Ratio	1.65	1.65	
100% Fan Hub Pressure Ratio	1.47	1.42	
Overall Pressure Ratio, OEI	26.5	30.6	+15.5%
Overall Pressure Ratio, Cruise	24.1	28.9	+19.9%
ΔSFC, Mission Weighted, %	Base	-8.5	
Engine Weight*, lbm	2625	2320	-12%
Engine Price*, \$ x 10^{-3}	2220	1800	-19%
Engine Maintenance*, \$/Engine·hr	66.70	50.20	-25%

*Not including PTO

TASK V - DEFINITION OF PREFERRED POWERPLANTS - Continued

MISSION ANALYSIS REFINEMENTS - Continued

Refined Prop/Shaft Engines

The major change to the prop/shaft engines was an increase in the OEI turbine temperature rating to 1371°C (2500°F). As in the case of the VIGV engine, this results in a core size reduction (17% for the ABC and 18% for the X-Wing) and better utilization of the core capability at cruise conditions. Another important change to the X-Wing prop/shaft engine was the elimination of the inlet particle separator, which was considered unnecessary for a core compressor of this size (50+ lbm/sec). Tables 84 and 85 compare the refined and Task III prop/shaft engines.

Weight and Economic Factors

Although the refined engines considered here were based on the Task II and Task III engines, there were some substantial changes in engine design (e.g., re-designed fan blades, elimination of the IPS from the X-Wing prop/shaft, the increased turbine temperature rating) that led to large variations in component size. Because of this, and to insure a fair comparison among systems, the weights, prices, and maintenance costs of the refined engines were recalculated at the component level of detail. Tables 86 and 87 provide the resulting mission size weight and economic data.

TABLE 84A. COMPARISON OF TASK III AND REFINED TASK V PROP/SHAFT ENGINES ABC ROTORCRAFT - CONSTANT OEI POWER

SI Units

	Task III Engine	Task V Refined Engine	Difference
OEI Rated T41, °C	1288	1371	+83°
OEI Output Power, kW	3795	3795	0
Maximum Core Speed, %	102.6	102.6	0
Design Cruise Equivalent Power, kW	2645	2645	0
Design Cruise T41, °C	1085	1205	+120°
100% Core $W\sqrt{\theta}/\delta$, kg/s	15.6	11.7	-25%
100% Core Pressure Ratio	22	22	
Overall Pressure Ratio, OEI	21.6	21.6	0
Overall Pressure Ratio, Cruise	19.1	19.7	+3.1%
ΔSFC, Mission Weighted	Base	-10.6	
Engine Weight, kg	530	425	-20%
Engine Price, \$ x 10^{-3}	940	820	-13%
Engine Maintenance, \$/Engine·hr	41.00	34.70	-15%

TABLE 84B. COMPARISON OF TASK III AND REFINED TASK V - PROP/SHAFT ENGINES ABC ROTORCRAFT - CONSTANT OEI POWER

English Units

	Task III Engine	Task V Refined Engine	Difference
OEI Rated T41, °F	2350	2500	+150°
OEI Output Power, hp	5090	5090	0
Maximum Core Speed, %	102.6	102.6	0
Design Cruise Equivalent Power, hp	3545	3545	0
Design Cruise T41, °F	1985	2205	+220°
100% Core $W\sqrt{\theta}/\delta$, lbm/sec	34.4	25.8	-25%
100% Core Pressure Ratio	22	22	
Overall Pressure Ratio, OEI	21.6	21.6	0
Overall Pressure Ratio, Cruise	19.1	19.7	+3.1%
ΔSFC, Mission Weighted	Base	-10.6	
Engine Weight, lbm	1170	940	-20%
Engine Price, \$ x 10^{-3}	940	820	-13%
Engine Maintenance, \$/Engine·hr	41.00	34.70	-15%

TABLE 85A. COMPARISON OF TASK III AND REFINED TASK V PROP/SHAFT ENGINES X-WING ROTORCRAFT - CONSTANT OEI POWER

SI Units

	Task III Engine	Task V Refined Engine	Difference
OEI Rated T41, °C	1288	1371	+83°
OEI Output Power, kW	8920	8920	0
Maximum Core Speed, %	102.6	102.6	0
Design Cruise Equivalent Power, kW	3250	3250	0
Design Cruise T41, °C	1020	1080	+60°
100% Core $W\sqrt{\theta}/\delta$, kg/s	32.6	26.7	-18.1%
100% Core Pressure Ratio	22	22	
Overall Pressure Ratio, OEI	21.6	22	+19%
Overall Pressure Ratio, Cruise	19.7	19.6	0
ΔSFC, Mission Weighted	Base	-14.5	
Engine Weight, kg	1086	690	-36%
Engine Price, \$ x 10^{-3}	1760	1365	-22%
Engine Maintenance, \$/Engine·hr	57.30	45.90	-20%

TABLE 85B. COMPARISON OF TASK III AND REFINED TASK V PROP/SHAFT ENGINES X-WING ROTORCRAFT - CONSTANT OEI POWER

English Units

	Task III Engine	Task V Refined Engine	Difference
OEI Rated T41, °F	2350	2500	+150°
OEI Output Power, hp	11960	11960	0
Maximum Core Speed, %	102.6	102.6	0
Design Cruise Equivalent Power, hp	4360	4360	0
Design Cruise T41, °F	1868	1974	+105°
100% Core $W\sqrt{\theta}/\delta$, lbm/sec	71.9	58.9	-18.1%
100% Core Pressure Ratio	22	22	
Overall Pressure Ratio, OEI	21.6	22	+1.9%
Overall Pressure Ratio, Cruise	19.7	19.6	0
Δ SFC, Mission Weighted	Base	-14.5	
Engine Weight, lbm	2395	1525	-36%
Engine Price, \$ x 10^{-3}	1760	1365	-22%
Engine Maintenance, \$/Engine·hr	57.30	45.90	-20%

TABLE 86. TASK V ABC REFINED ENGINES WEIGHT AND ECONOMIC DATA*		
(Final Mission Size)		
Engine	Prop/Shaft	Convertible
Engine weight without PTO, kg (lbm)	404 (890)	549 (1210)
Weight of PTO, Gear and Shafting, kg (lbm)	---	63 (140)
Engine price, without PTO $ x 10^{-3}	795	1135
Price of PTO Gear and Shafting, $ x 10^{-3}	---	43
Engine maintenance cost without PTO, $/hr	33.70	43.70
Maint. cost of PTO Gear and Shafting, $/hr	---	1.20

*Economic data is furnished by General Electric Company for study purposes only in the performance of this contract.

TABLE 87. TASK V X-WING REFINED ENGINES WEIGHT AND ECONOMIC DATA*		
(Final Mission Size)		
Engine	Prop/Shaft	Convertible
Engine weight without PTO, kg (lbm)	594 (1310)	968 (2135)
Weight of PTO, Gear and Shafting, kg (lbm)	---	125 (275)
Engine price, without PTO $ x 10^{-3}	1255	1720
Price of PTO Gear and Shafting, $ x 10^{-3}	---	50
Engine maintenance cost without PTO, $/hr	42.20	48.00
Maint. cost of PTO Gear and Shafting, $/hr	---	2.20

*Economic data is furnished by General Electric Company for study purposes only in the performance of this contract.

TASK V - DEFINITION OF PREFERRED POWERPLANTS - Continued

MISSION ANALYSIS REFINEMENTS - Continued

As mentioned above, the weights and prices of transmission elements were also revaluated at this point in the study, especially vis-a-vis the unique elements required by the VIGV and prop/shaft systems. The weight and price of the elements common to all systems (main reduction gear, for example) were not revised, but left as calculated by Boeing Vertol. The unique items, such as engine power takeoff (PTO) gearing and propeller transmissions were revised to bring them in line with prior General Electric experience and studies.

Tables 88 and 89 provide breakdowns of the contributions of the various propulsion system elements to aircraft weight, price, and maintenance. These tables are for the refined engines scaled into the original Task II and III rotorcraft; gross weight has not been adjusted for the savings due to the refined engines. These tables show the relative importance of the major propulsion system elements, but are not in final mission size.

TABLE 88. PROPULSION SYSTEM WEIGHT, PRICE, AND MAINTENANCE COMPARISON ABC ROTORCRAFT - REFINED ENGINES

(Nominal Size)

	VIGV Engines		Prop/Shaft Engines	
Gross Weight, kg (lbm)	16580	(36550)	16190	(35690)
Propulsion Weights, kg (lbm)/aircraft				
Engines	1165	(2570)	855	(1880)
Installation	275	(610)	150	(330)
Propellers	-		350	(780)
Drives	1435	(3160)	1680	(3700)
Total	2875	(6340)	3035	(6690)
Propulsion Prices $ x 10^{-3}/aircraft				
Engines	2350		1640	
Installations	195		120	
Propellers	-		100	
Drives	465		660	
Total	3010		2520	
Propulsion Maintenance $/Aircraft·hr				
Engines	90		69	
Installation	4		2	
Propellers	-		4	
Drives	22		28	
Total	116		103	

TABLE 89. PROPULSTION SYSTEM WEIGHT, PRICE, AND MAINTENANCE COMPARISON X-WING ROTORCRAFT - REFINED ENGINES

(Nominal Size)

	VIGV Engines	Prop/Shaft Engines
Gross Weight, kg (lbm)	21645 (47720)	23735 (52330)
Propulsion Weights, kg (lbm)/aircraft		
Engines	2105 (4640)	1390 (3050)
Installation	510 (1120)	195 (430)
Propellers	-	715 (1580)
Drives	2060 (4540)	3505 (7740)
Total	4675 (10300)	5805 (12800)
Propulsion Prices $ x 10^{-3}/Aircraft		
Engines	3600	2730
Installation	350	150
Propellers	-	390
Drives	670	1440
Total	4620	4710
Propulsion Maintenance $/Aircraft·hr		
Engines	100	92
Installation	6	2
Propellers	-	5
Drives	34	58
Total	140	157

ROTORCRAFT EVALUATION WITH REFINED POWERPLANTS

The four refined powerplants were evaluated in terms of their effect on mission parameters by applying the mission trade factors of the preceding section individually to the changes in weight, fuel consumption, price, and maintenance cost, and then summing the resulting changes in gross weight, acquisition cost, fuel consumption, and DOC. Engine size and aircraft subsystem weights were then recalculated for the resulting lower gross weights.

Tables 90 and 91 provide the final mission comparison between the prop/shaft powered aircraft and the convertible engine powered vehicles. Tables 92 and 93 summarize the qualitative factors that were considered in the comparison between systems. For the ABC (Table 90), all the quantitative factors favor the propeller configuration, which shows a DOC advantage of 11% and a block fuel reduction of 14% relative to the convertible engine. For the X-Wing rotorcraft, the prop/shaft has a 6% DOC and 17% block fuel advantage, although the acquisition cost of the two aircraft are virtually the same, and the prop/shaft configuration has a 2% higher gross weight.

TABLE 90. MISSION ANALYSIS COMPARISON - PROP/SHAFT AND VIGV

(ABC Rotorcraft, Refined Engines)

Standard Day, 370 km (200 nmi) Mission

65% Load Factor, $.528/l ($2.00/gal) Fuel

1981 Economy

	Task II VIGV Engine	Task III Prop/Shaft Engine	% - Difference
Aircraft Gross Weight kg (lbm)	15610 (34410)	15300 (33730)	-2.0
Aircraft Acquisition Cost, $ x 10^{-6}	7.15	6.69	-6.4
Block Fuel, kg (lbm)	940 (2070)	800 (1770)	-14.4
Direct Operating Cost ¢/seat·km (¢/seat·nmi)	8.5 (15.7)	7.6 (14.0)	-10.8

TABLE 91. MISSION ANALYSIS COMPARISON - PROP/SHAFT AND VIGV

(X-Wing Rotorcraft, Refined Engines)

Standard Day, 833 km (450 nmi) Mission

85% Load Factor, \$.594/l (\$2.25/gal) Fuel

1981 Economy

	Task II VIGV Engine	Task III Prop/Shaft Engine	% Difference
Aircraft Gross Weight, kg (lbm)	19935 (43950)	20370 (44900)	+2.2
Aircraft Acquisition Cost, \$ x 10^{-6}	9.89	9.83	-0.6
Block Fuel, kg (lbm)	1750 (3860)	1450 (3195)	-17.2
Direct Operating Cost ¢/seat·km (¢/seat·nmi)	7.5 (13.9)	7.1 (13.1)	-5.8

TABLE 92. QUALITATIVE SECONDARY EVALUATION CRITERIA ABC ROTORCRAFT

	VIGV Fan/Shaft	Prop/Shaft
Community Acceptance	Closed VIGV Noise a Concern	Prop Unloaded at Takeoff. Probably OK.
Passenger Acceptance	Equivalent to Helicopter	Cabin Noise and Vibration a Concern
Reliability	Equivalent to Turbofan	Additional Components (Gearing and Prop) a Concern
Operability	Equivalent	Equivalent
Program Risk	Closed VIGV Operation a Concern.	Prop Installation a Concern.

TABLE 93. QUALITATIVE SECONDARY EVALUATION CRITERIA X-WING ROTORCRAFT

	VIGV Fan/Shaft	Prop/Shaft
Community Acceptance	Closed VIGV Noise a Concern.	Props Unloaded at Takeoff. Probably OK.
Passenger Acceptance	Equivalent to Helicopter	Cabin Noise and Vibration a Concern.
Reliability	Equivalent to Turbofan	Large number of Additional Components a Concern.
Operability	Equivalent	Equivalent
Program Risk	Closed VIGV Operation a Concern	Prop Installation Presents Major Aero. and Structural Design Problem.

TASK V - DEFINITION OF PREFERRED POWERPLANTS - Continued

ROTORCRAFT EVALUATION WITH REFINED POWERPLANTS - Continued

A discussion of the qualitative criteria is contained in the following paragraphs.

Community acceptance refers primarily to noise. Today's helicopter rotors dominate noise perceived on the ground and the engine noise is unimportant. It is assumed here that advanced rotorcraft rotor noise will be lower and that differences between propulsion systems will therefore be a consideration. The convertible turbofan VIGV is a possible problem since the high turbulence and wake interference with IGV and EGV closed are strong noise sources. The propeller thrust requirements for the rotorcraft are modest at takeoff compared to climb/cruise. Therefore the propeller would tend to be a low noise source.

Passenger acceptance refers primarily to cabin noise although for the ABC in the commercial transport mission, the psychological reaction of passengers to aircraft configuration is also a factor. The turbofan might have the edge over the prop although it can be argued that commuter turboprops have gained wide acceptance. For the prop/shaft even though the props are mounted aft to avoid a cabin noise problem, there may still be some vibration transmitted through the structure. In any event the noise concern drives the propeller installation.

Reliability of the prop/shaft system was shown in Task III to be somewhat lower than VIGV turbofan, primarily due to the larger number of components (gears, shafts, props) required, each with a finite failure rate. The reliability difference is expected to be greater for the X-Wing because of the complexity of the propeller drive train.

Operability refers mainly to thrust modulation and thrust reversal capability. The prop/shaft has the capability of modulating through zero to reverse whereas the convertible VIGV turbofan does not. However, for commercial operation, this capability is not required. For military applications thrust modulation without vehicle attitude change is considered necessary to maintain a steady gun platform. Vectored exhaust provides a potential method of providing this capability with the VIGV turbofan.

ROTORCRAFT EVALUATION WITH REFINED POWERPLANTS - Continued

Program Risk - The VIGV turbofan in the takeoff, closed VIGV position has technical risks to be explored in test programs like the TF34 CEST. The degree of VIGV closure may be limited by aeromechanical buffeting/instability, hot gas reingestion and noise levels.

For the prop/shaft, the selection of a good installation from the aspects of noise, rotor aero interaction, aircraft balance weight, structural design and cabin noise is a critical design problem. This is more so in the X-Wing than the ABC.

RECOMMENDED POWERPLANTS

ABC Rotorcraft

As shown above, all the quantitative factors strongly favor the propeller powered version of the ABC. The qualitative evaluation criteria do not favor either powerplant; both have advantages and disadvantages. The single pusher propeller installation has received considerable favorable attention by airframers in recent years and although it is a minor concern, it is considered entirely feasible with development effort. Cabin noise and vibration is a minor problem also, but it too can be handled with development. The fan pressure ratio of 1.36 picked was near optimum as shown in Task IV, therefore the comparison of the VIGV turbofan vs. the prop fan was fair in that respect.

There is considerable opposition to the selection of a propeller from the military on the basis of hazard to personnel, interference with foliage etc. during close to the ground operation, and an undesirable radar signal. These factors would be crucial in the selection of a VIGV turbofan or shrouded propeller over the conventional propeller if one envisions any civil high speed rotorcraft as an evolution from a military application.

On the basis of the qualitative and quantitative factors the prop/shaft is recommended for the Civil ABC Rotorcraft. The relationship/commonality of this rotorcraft to a military rotorcraft could alter that selection. A sketch of the selected engine is provided as Figure 65, performance data in Table 94 and Appendix A.

X-Wing Rotorcraft

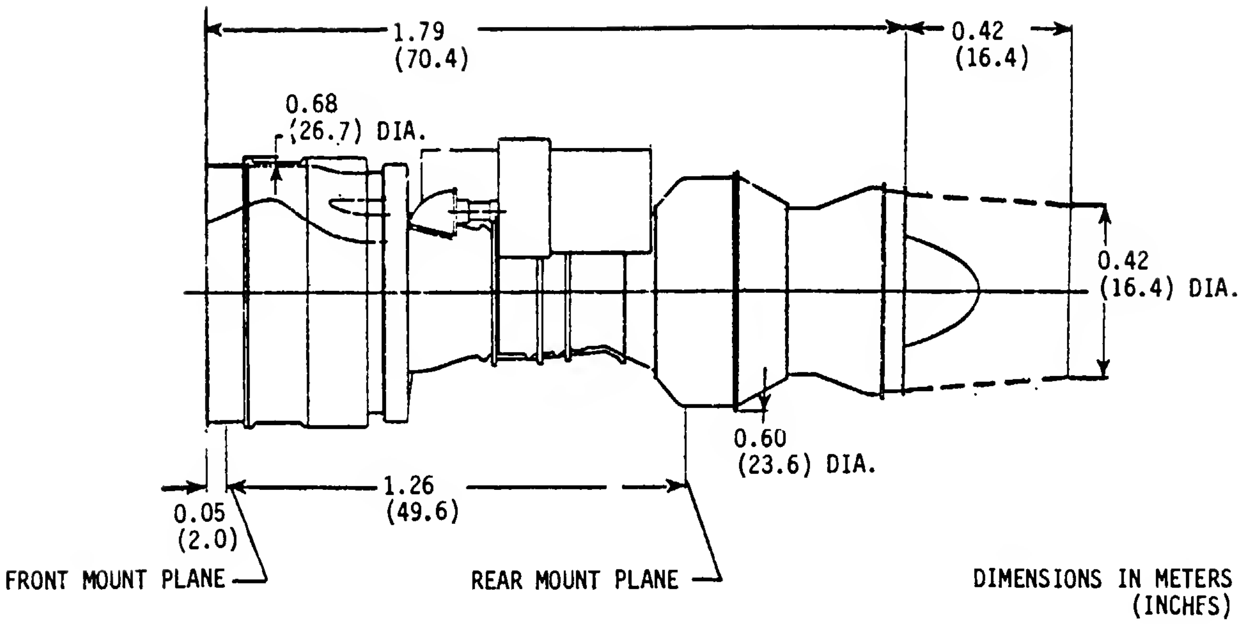
The VIGV Turbofan is selected for the X-Wing rotorcraft on the basis of a number of qualitative factors which are believed to override the fuel consumption and DOC advantages of the Prop/Shaft for this application.

A discussion of some of the factors entering into this decision follows:

1. Uncertainties in Economic Assumptions
   At the outset of this study, in a climate of rapidly rising fuel costs, a base fuel cost of \$.528/l (\$2.00/gal) was selected. In retrospect, considering the more stable prices over the past year, this value seems high. A lower fuel cost erodes the advantage of the prop/shaft, as does lower utilization. (In a military application of this aircraft, utilization would likely be on the order of 300-400 hr/yr instead of 2000). Figure 66 shows the sensitivity of the DOC result to fuel cost and utilization.

   Engine, propeller, and transmission pricing is another area of uncertainty. We are dealing with unprecedented systems in both the VIGV and prop/shaft configurations, and costs are the most difficult parameters to estimate accurately. Accordingly, Figure 67 shows the effect of a ±10% variation in the price and maintenance cost of the prop/shaft propulsion system (less the main rotor drive).

2. Propeller Installation
   The prop/shaft installation in the X-Wing is deemed to be heavy and awkward. It is driven by a concern over potential problems such as cabin noise and rotor slipstream interference with the propellers. The transmission involves a large number of gears, shafts, and bearings in close proximity to the passenger compartment. It may well contribute to problems of passenger comfort (noise and vibration), safety, and reliability.



ENGINE WEIGHT = 403kg (888 lbm) EXCLUDING TAILPIPE AND A/C ACCESSORIES

Figure 65. Task V ABC Prop/Shaft Engine

3. Potential for Higher Flight Speed
The X-Wing nominal cruise speed of 741 km/h (400 kts) could be extended upwards, which is a natural turbofan operating regime; 741 km/h (400 kt) is conservative in light of the capabilities being forecast for X-Wing rotorcraft. Figure 68 documents the decreasing thrust sfc advantage of the prop as flight speed is increased to 926 km/h (500 kt), on a design point basis; i.e., the engines are resized to match the increased cruise speed.

4. Military Commonality

The USN and DARPA are strong advocates of the X-Wing type as a carrier based rotorcraft system. Current developments indicate that these agencies will first develop a viable 30000 lb GW prototype, from which a civil model may evolve. There is a strong preference for convertible turbofans for safety and observability reasons and therefore the evolutionary civil rotorcraft will use the same powerplant. It is of interest to note that Boeing Vertol calculations indicate that the civil X-Wing 48 PAX rotorcraft gross weight is consistent with the 30000 lb military prototype when payload, range and OEI sizing practice differences are taken into account.

TABLE 94A. FINAL, MISSION SIZE PROP/SHAFT ENGINE FOR ABC ROTORCRAFT

SI Units

	OEI Hover ISA 15°C	Normal Takeoff ISA	Design Cruise ISA 10°C	Mid-Cruise ISA
Altitude, m	0	0	3048	3048
Flight Speed, km/h	0	0	463	463
Output Power, kW	3585	1555	2460	2255
Equivalent Power, kW	3715	1620	2500	2275
Thrust, N	1960	910	220	155
Fuel Flow, kg/h	870	460	575	530
Turbine Inlet Temp, °C	1371	1024	1207	1132
Cycle Pressure Ratio	21.6	13.8	19.7	19.0
Fuel Heating Value, kJ/kg	42800			
Output Speed, rad/s	1565	1565	1325	1280
Inlet Separator				
Pressure Loss, %	1.7	0.8	1.5	1.4
Bleed Flow, %	16.7	16.7	16.7	16.7
Compressor				
Number of Stages	5 Axial + 1 Centrifugal			
Inlet Flow, kg/s	10.6	7.6	7.8	7.7
Inlet Corrected Flow, kg/s	11.0	7.7	10.3	10.0
Pressure Ratio	22	13.9	20.0	19.2
HP Turbine				
Number of Stages	2			
Pressure Ratio	4.7	4.5	4.8	4.8
LP Turbine				
Number of Stages	3			
Flow Function $(W\sqrt{T}/P)$, kg °K$^{1/2}$ m^2/(kN·s)	.82	.78	.83	.83
Specific Work (Δh) kJ/kg	361	205	319	293
Inlet Temperature, °C	896	646	768	713
Mean Pitch Line Wheel Speed, m/s	314	314	265	256
Loading*(ψ p)	.61	.35	.75	.74
Pressure Ratio	4.0	2.8	4.0	3.8
Adiabatic Efficiency	.910	.872	.908	.908
Exit Mach Number	.45	.29	.45	.43
Exhaust System				
LP Turbine Duct Pressure Loss, %	1.0	1.9	0.9	0.9
Nozzle Pressure Ratio, $P_8/P_{ambient}$	1.08	1.03	1.08	1.07
Exhaust Temperature, °C	588	460	491	452

$$*\psi_p = \frac{gJ\,\Delta h}{2\,(U_p)^2}$$

TABLE 94B. FINAL, MISSION SIZE PROP/SHAFT ENGINE FOR ABC ROTORCRAFT

English Units

	OEI Hover ISA +27°F	Normal Takeoff ISA	Design Cruise ISA + 18°F	Mid-Cruise ISA
Altitude, ft	0	0	10000	10000
Flight Speed, kt	0	0	250	250
Output Power, hp	4810	2085	3300	3025
Equivalent Power, hp	4985	2170	3350	3050
Thrust, lbf	440	205	50	35
Fuel Flow, lbm/hr	1920	1015	1265	1165
Turbine Inlet Temp, °F	2500	1875	2205	2070
Cycle Pressure Ratio	21.6	13.8	19.7	19.0
Fuel Heating Value, BTU/lbm	18400			
Output Speed, rpm	14950	14950	12630	12210
Inlet Separator				
Pressure Loss, %	1.7	0.8	1.5	1.4
Bleed Flow, %	16.7	16.7	16.7	16.7
Compressor				
Number of Stages	5 Axial + 1 Centrifugal			
Inlet Flow, ibm/sec	23.3	16.8	17.1	17.0
Inlet Corrected Flow, lbm/sec	24.3	16.9	22.7	22.1
Pressure Ratio	22	13.9	20.0	19.2
HP Turbine				
Number of Stages	2			
Pressure Ratio	4.7	4.5	4.8	4.8
LP Turbine				
Number of Stages	3			
Flow Function $(W\sqrt{T}/P)$, lbm °R½ in²/(lbf·sec)	16.7	15.9	16.9	16.9
Specific Work (Δh) BTU/lbm	155	88	137	126
Inlet Temperature, °F	1645	1195	1415	1315
Mean Pitch Line Wheel Speed, ft/sec	1030	1030	870	840
Loading *(ψp)	.61	.35	.75	.74
Pressure Ratio	4.0	2.8	4.0	3.8
Adiabatic Efficiency	.910	.872	.908	.908
Exit Mach Number	.45	.29	.45	.43
Exhaust System				
LP Turbine Duct Pressure Loss, %	1.0	1.9	0.9	0.9
Nozzle Pressure Ratio, $P_8/P_{ambient}$	1.08	1.03	1.08	1.07
Exhaust Temperature, °F	1090	860	915	845

$$* \psi_p = \frac{gJ\Delta h}{2\,(U_p)^2}$$

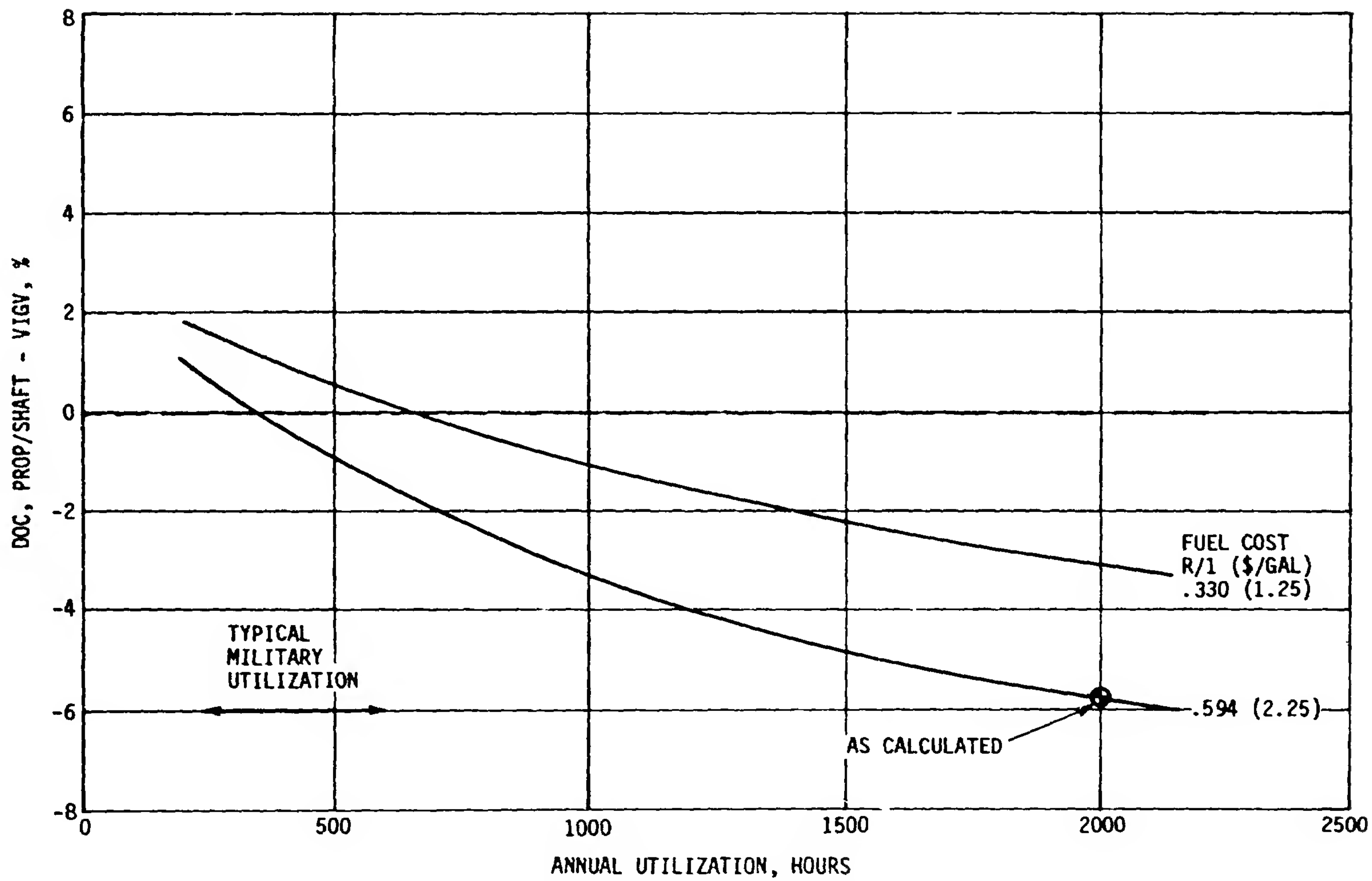


Figure 66. X-Wing DOC Trends vs Utilization and Fuel Cost

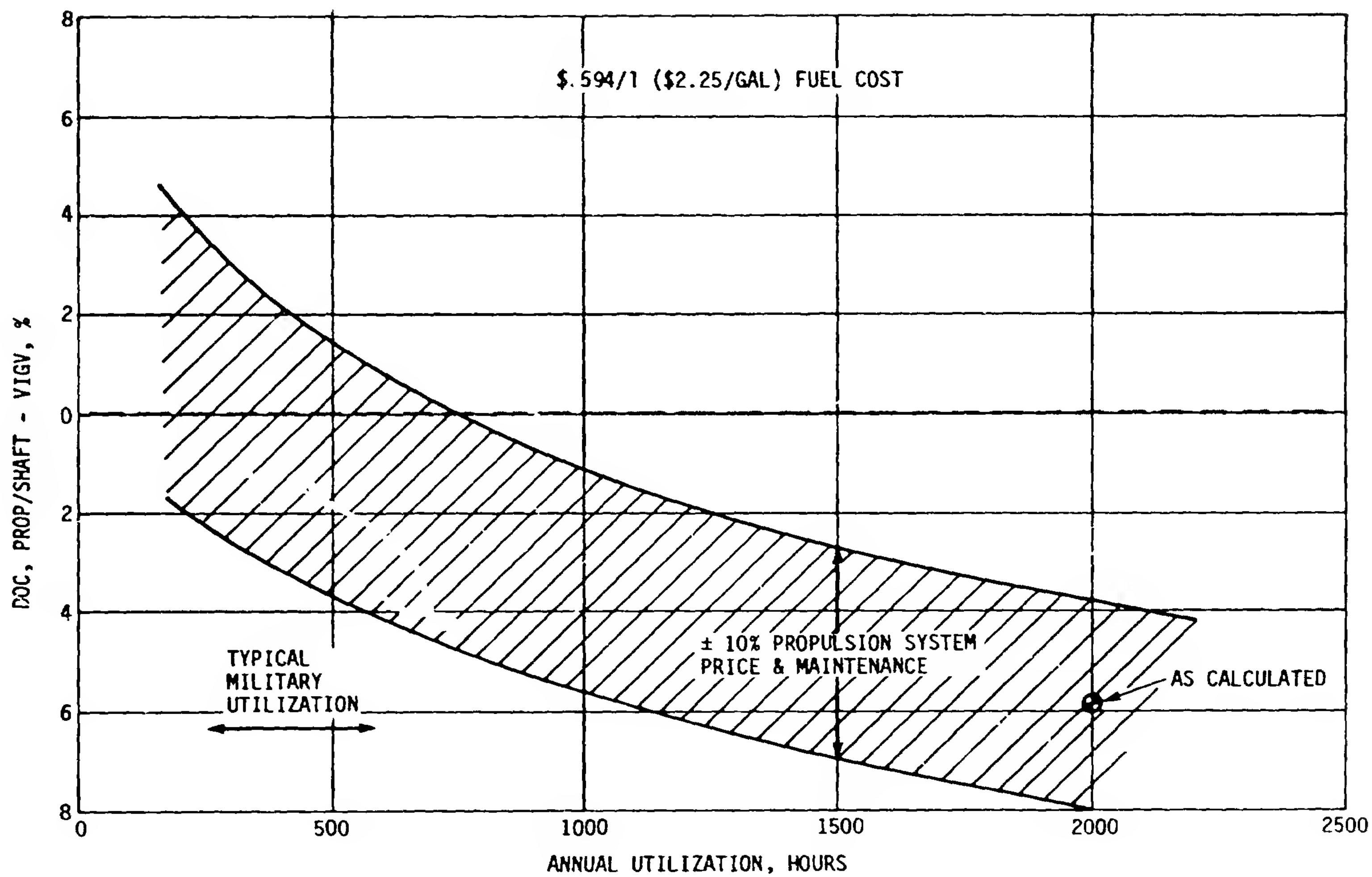


Figure 67. X-Wing DOC Trends vs Utilization and Propulsion System Prices

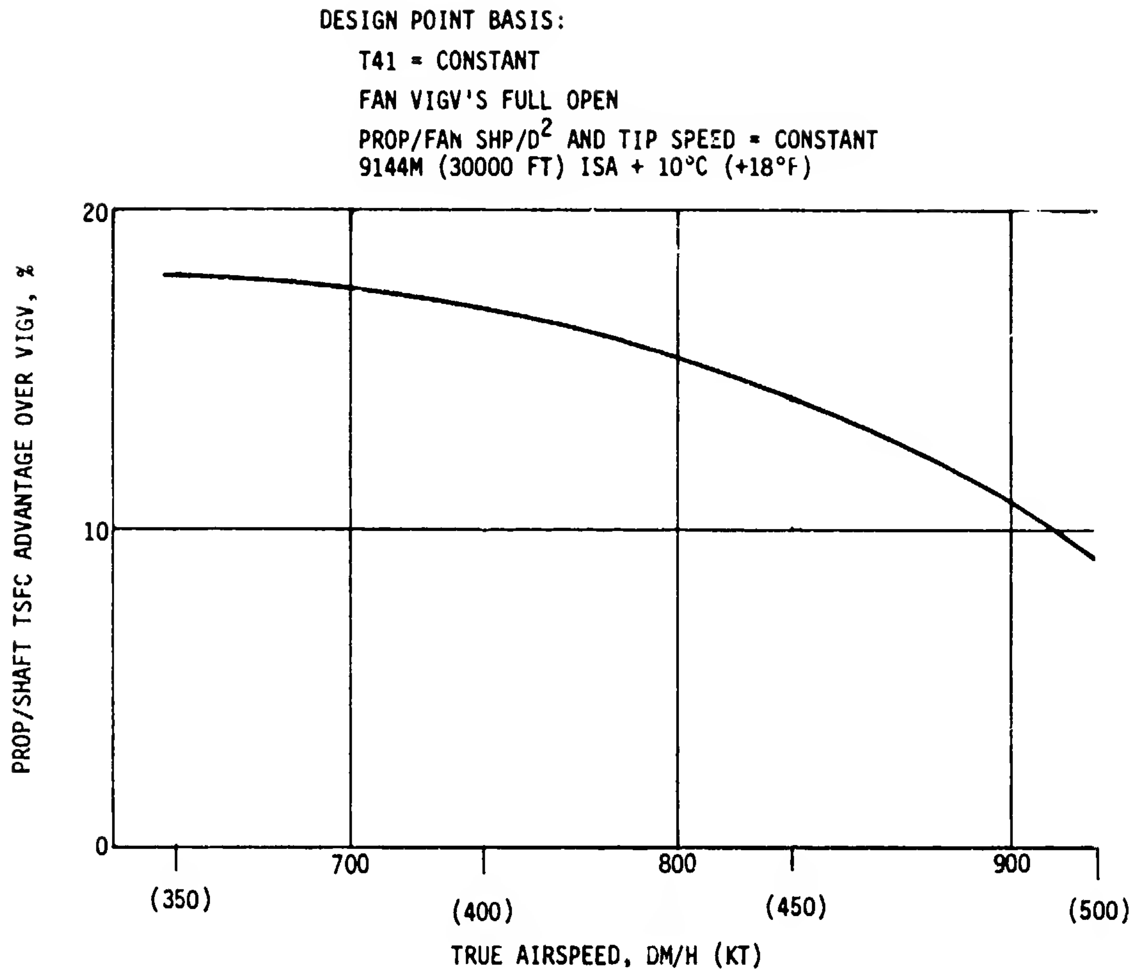


Figure 68. TSFC Trend With Flight Speed - X-Wing Rotorcraft

Based on the above considerations, General Electric believes both configurations, prop/shaft and VIGV turbofan, are deserving of continued study for the X-Wing application, but has selected the VIGV turbofan as the preferred powerplant.

Figure 69 shows the prop/shaft engine with installation dimensions. Figure 70 shows the flowpath and exterior dimensions of the VIGV turbofan for the X-Wing. Table 95 and Appendix B provide engine performance data.

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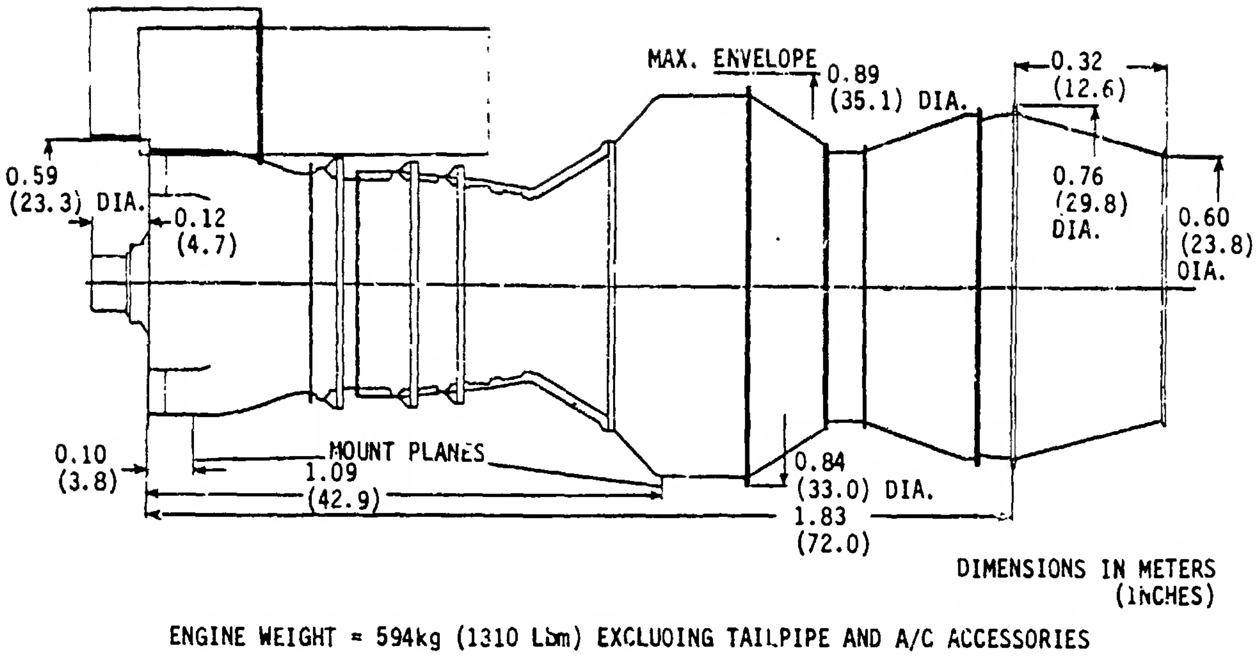

Figure 69. Task V X-Wing Prop/Shaft Engine

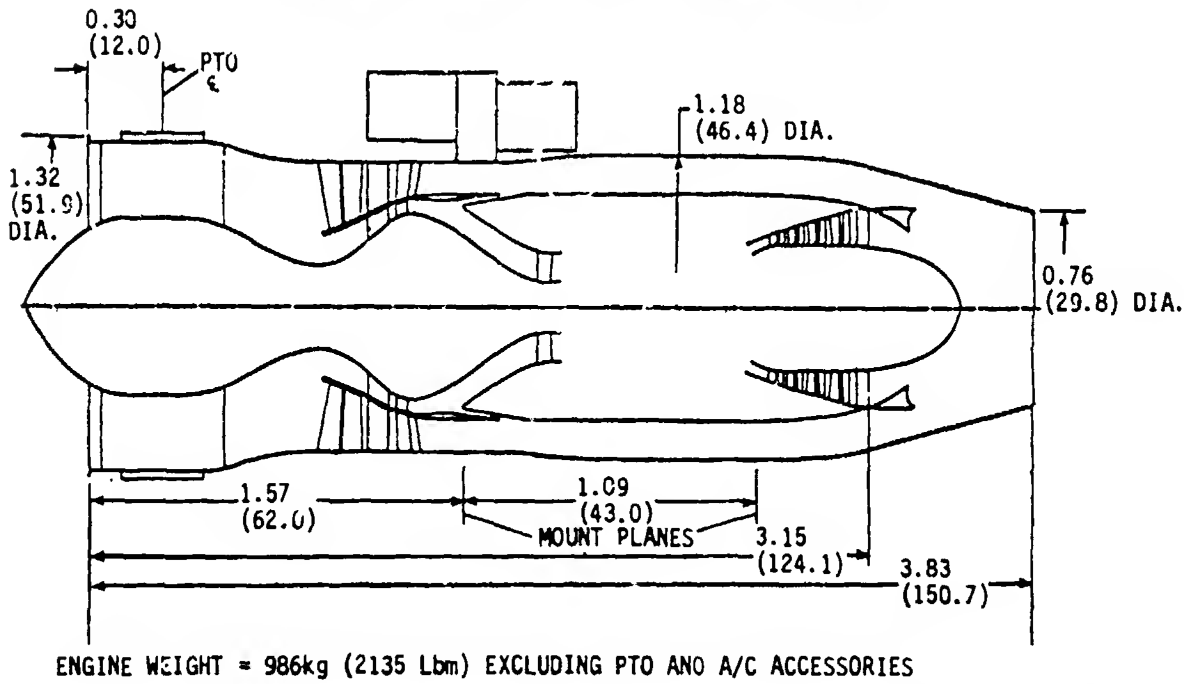

Figure 70. Task V X-Wing Convertible Engine

TABLE 95A. FINAL, MISSION SIZE VIGV CONVERTIBLE TURBOFAN ENGINE FOR X-WING ROTORCRAFT

SI Units

	OEI Hover ISA 15°C	Normal Takeoff ISA	Design Cruise ISA 10°C	Mid Cruise ISA
Altitude, m	0	0	9144	9144
Flight Speed, km/n	0	0	741	741
Output Power, kW	7415	3480	231	224
Fan Windage, kW	760	800	-	-
Thrust, N	7250	4270	10590	10140
Fuel Flow, kg/h	1975	1240	710	680
Turbine Inlet Temp, °C	1371	1079	1124	1063
Cycle Pressure Ratio	30.6	21.9	28.9	28.3
Fuel Heating Value, kJ/kg	42800			
Fan Outer Panel				
Number of Stages	1			
Inlet Flow, kg/s			45.8	46.3
Inlet Corrected Flow, kg/s			109	107
Inlet Corrected Tip Speed, m/s			1305	1330
Pressure Ratio			1.65	1.62
Adiabatic Efficiency			.883	.862
Rotational Speed, rad/s	670	670	670	670
VIGV Closure, °	Full Closed →		0	8
Fan Inner Panel				
Number of Stages	1			
Inlet Flow, kg/s	27.3	28.6	12.6	13.2
Inlet Corrected Flow, kg/s	26.0	28.6	29.8	30.3
Inlet Corrected Tip Speed, m/s	229	235	247	251
Pressure Ratio	1.42	1.43	1.[illegible]6	1.48
Adiabatic Efficiency	.905	.898	.882	.873
Exit Bleed, %	0	25	11	14
Duct Pressure Loss, %	2	1.2	1.7	1.7
Compressor				
Number of Stages	10			
Inlet Flow, kg/s	27.3	21.5	11.2	11.4
Inlet Corrected Flow, kg/s	21.2	16.1	19.6	19.2
Pressure Ratio	22	15.4	20.1	19.5
HP Turbine				
Number of Stages	2			
Pressure Ratio	5.7	5.6	5.5	5.5
LP Turbine				
Number of Stages	4			
Flow Function ($W\sqrt{T}/P$), lbm °R½ in²/lbf sec)	1.77	1.72	1.72	1.72
Specific Work (Δh), kJ/kg	354	247	247	235
Inlet Temperature, °C	860	652	682	638
Mean Pitch Line Wheel Speed, m/s	195	195	195	195
Loading* (ψ p)	1.15	.80	.80	.76
Pressure Ratio	4.2	3.3	3.2	3.2
Adiabatic Efficiency	.896	.897	.897	.895
Exit Mach No.	.38	.29	.[illegible]3	.28
Exhaust System				
Fan Duct Pressure Loss, %			1.9	1.9
LP Turbine Duct Pressure Loss, %	1.0	.6	.6	.6
Mixer Effectiveness, %			65	65
Post-Mixer Pressure Loss, %			.15	.15
Mean Exhaust Temperature, °C	557	429	374	357

$$* \; \psi_p = \frac{J \Delta h}{\frac{1}{2} (U_p)^2}$$

TABLE 95B. FINAL, MISSION SIZE VIGV CONVERTIBLE TURBOFAN ENGINE FOR X-WING ROTORCRAFT

English Units

	OEI Hover ISA +27°F	Normal Takeoff ISA	Design Cruise ISA +18°F	Mid Cruise ISA
Altitude, ft	0	0	30000	30000
Flight Speed, kt	0	0	400	400
Output Power, hp	9945	4670	310	300
Fan Windage, hp	1020	1075	-	-
Thrust, lbf	1630	960	2380	2280
Fuel Flow, lbm/hr	4350	2735	1570	1500
Turbine Inlet Temp, °F	2500	1975	2055	1945
Cycle Pressure Ratio	30.6	21.9	28.9	28.3
Fuel Heating Value, BTU/lbm	18400			
Fan Outer Panel				
Number of Stages	1			
Inlet Flow, lbm/sec			101	102
Inlet Corrected Flow, lbm/sec			241	236
Inlet Corrected Tip Speed, ft/sec			1305	1330
Pressure Ratio			1.65	1.62
Adiabatic Efficiency			.883	.862
Rotational Speed, rpm	6400	6400	6400	6400
VIGV Closure, °	Full Closed		0	8
Fan Inner Panel				
Number of Stages	1			
Inlet Flow, lbm/sec	60.1	63.0	27.7	29.0
Inlet Corrected Flow, lbm/sec	61.7	63.0	65.8	66.8
Inlet Corrected Tip Speed, ft/sec	750	770	810	825
Pressure Ratio	1.42	1.43	1.46	1.48
Adiabatic Efficiency	.905	.898	.882	.873
Exit Bleed, %	0	25	11	14
Duct Pressure Loss, %	2	1.2	1.7	1.7
Compressor				
Number of Stages	10			
Inlet Flow, lbm/sec	60.1	47.4	24.6	25.1
Inlet Corrected Flow, lbm/sec	46.8	35.4	43.3	42.4
Pressure Ratio	22	15.4	20.1	19.5
HP Turbine				
Number of Stages	2			
Pressure Ratio	5.7	5.6	5.5	5.5
LP Turbine				
Number of Stages	4			
Flow Function $(W\sqrt{T}/P)$, lbm $°R^{\frac{1}{2}}$ in^2/lbf·sec)	36.1	35.1	35.1	35.0
Specific Work (Δh), BTU/lbm	152	106	106	101

TABLE 95B. FINAL, MISSION SIZE VIGV CONVERTIBLE TURBOFAN ENGINE FOR X-WING ROTORCRAFT - Continued

English Units

	OEI Hover ISA +27°F	Normal Takeoff ISA	Design Cruise ISA +18°F	Mid Cruise ISA
LP Turbine - Continued				
Inlet Temperature, °F	1580	1205	1260	1180
Mean Pitch Line Wheel Speed, ft/sec	640	640	640	640
Loading* (ψp)	1.15	.80	.80	.76
Pressure Ratio	4.2	3.3	3.2	3.2
Adiabatic Efficiency	.896	.897	.897	.895
Exit Mach No.	.38	.29	.28	.28
Exhaust System				
Fan Duct Pressure Loss, %			1.9	1.9
LP Turbine Duct Pressure Loss, %	1.0	.6	.6	.6
Mixer Effectiveness, %			65	65
Post-Mixer Pressure Loss, %			.15	.15
Mean Exhaust Temperature, °F	1035	805	705	675

$$*\psi_p = \frac{gJ\Delta h}{2\,(U_p)^2}$$

TASK VI - BENEFIT ASSESSMENT

TASK I REFINEMENTS

The Task I results were adjusted to the extent of substituting separate turboshaft engines which, like the VIGV and prop/shaft engines, were uprated to 1371°C (2500°F) at OEI. This change had a smaller impact on the separate engine powered vehicles because the thrust producing engines were unaffected. Table 96 summarizes the impact of this change on the aircraft.

TABLE 96. IMPACT OF 1371°C (2500°F) OEI RATING ON TASK ROTORCRAFT

(Separate Engines)

		ABC	X-Wing
OEI T41, °C (°F)	1288 (2350)	1371 (2500)	1371 (2500)
ΔGross Weight, %	Base	-3.8	-6.8
ΔAcquisition Cost, %	Base	-4.6	-7.3
ΔBlock Fuel, %	Base	-6.[illegible]	-5.4
ΔDOC, %	Base	-4.9	-6.2

ROTORCRAFT COMPARISON

The benefits of the preferred powerplants relative to the separate engine baselines are summarized in Table 97 for the ABC and Table 98 for the X-Wing. (The convertible engine ABC and prop/shaft X-Wing are also shown for completeness). In both aircraft, the preferred powerplants provide a DOC advantage in excess of 20% over the Task I separate engine powered baseline aircraft, as well as substantial acquisition cost and block fuel savings.

The qualitative factors considered do not show a strong bias in favor of any of the systems. There are compensating advantages and disadvantages in all 1 to 1 comparisons. Both propellers and VIGV fans are expected to create some noise problems in comparison to the separate engines, but are expected to show significant improvements in reliability through reduction in the number of components.

TABLE 97. TASK VI FINAL BENEFIT ASSESSMENT (ABC ROTORCRAFT - REFINED ENGINES)

Standard Day, 370 km (200 nmi) Mission

65% Load Factor, \$.528/l (\$2.00/gal) Fuel

1981 Economy

	Separate Engines	Convertible Engines	Prop/Shaft Engines (Preferred Powerplant)
Quantative Factors			
ΔGross Weight, %	Base	-7.2	-9.1
ΔAcquisition Cost, %	Base	-12.1	-17.7
ΔBlock Fuel, %	Base	-15.1	-27.3
ΔDOC, %	Base	-12.7	-22.1
Qualitative Factors			
Community Acceptance	Base	-	-
Passenger Acceptance	Base		
Reliability	Base	++	++
Operability	Base		+
Program Risk	Base	-	-

TABLE 98. TASK VI FINAL BENEFIT ASSESSMENT (X-WING ROTORCRAFT - REFINED ENGINES)

Standard Day, 833 km (450 nmi) Mission

85% Load Factor, \$.594/l (\$2.25/gal) Fuel

1981 Economy

	Separate Engines	Convertible Engines (Preferred Powerplant)	Prop/Shaft Engines
Quantitative Factors			
ΔGross Weight, %	Base	-15.3	-13.4
ΔAcquisition Cost, %	Base	-18.1	-18.6
ΔBlock Fuel, %	Base	-16.1	-30.6
ΔDOC, %	Base	-20.8	-25.3
Qualitative Factors			
Community Acceptance	Base	-	-
Passenger Acceptance	Base		
Reliability	Base	++	+
Operability	Base		+
Program Risk	Base	-	-

TASK VII - RECOMMENDATIONS FOR FUTURE RESEARCH

The convertible engine types selected as preferred powerplants are the VIGV turbofan and the prop/shaft. The design of the powerplants, including the transmissions, was reviewed with the intent of identifying technology which requires R&D prior to incorporation into a rotorcraft powerplant design.

The core engines used in this study all assume advanced turbomachinery components. However, the technology for core development is not unique to the rotorcraft application and therefore were not considered in the present context The focus is on those elements of the power train which are unique to rotorcraft engines and which would not be developed for other applications. A list of critical technologies, Table 99, was compiled by reviewing the powerplant and transmission design with Boeing Vertol and General Electric component design engineers.

A brief discussion of each of the items follows.

VIGV FAN

The VIGV fan is the heart of a convertible fan/shaft engine design, but many of its characteristics are not well understood at this time. In the area of aerodynamics, research is required to fully understand the impact of the presence of the splitter in the fan stream; to optimize the blade design, taking advantage of the added flexibility in airfoil design the splitter allows; to understand and improve fan performance with inlet and exit guide vanes far closed; to optimize the flowpath for minimum losses and good FOD separation. In the area of aero mechanics, there are questions of blade stall and stress in the far- and full-closed IGV modes. The acoustic characteristics of a fan stage like this in the closed VIGV modes are almost completely unknown.

INTEGRATED ENGINE AND ROTORCRAFT CONTROL

The design of an integrated propulsion and rotorcraft control system is critical to the successful development of these advanced rotorcraft. Systems studies are required to determine the optimum control strategies; how to measure and/or calculate engine output and match it to rotorcraft requirements; how to respond in OEI situations. There is an opportunity for the application of the concept of distributed control, with fundamental questions to be answered about the interactions among various control elements. Development of a real-time, dynamic simulation of the aircraft and propulsion system would be an invaluable aid in control system research.

BLEED COMPRESSOR

The supply of bleed air to the rotor system is fundamental to the operation of the X-Wing rotor. The flow and pressure ratio rotor demand in the takeoff, climb and conversion rotary wing modes and in the conversion and cruise fixed wing mode must be established and then matched to the capabilities of auxiliary compressors. This study includes the selection of a compressor type, consideration of variable geometry, and selection of an output speed mode compatible with efficient bleed compressor and fan operation.

EXHAUST FOR TORQUE REACTION FUNCTION

There are several configurations proposed for X-Wing anti-torque systems. The Boeing Vertol input for this study was a tail rotor flush-mounted in the vertical stabilizer (Fenestron type propeller in French helicopters). Lockheed and others at DARPA have proposed using the engine exhaust, vectored through a "venetian blind" in the vertical stabilizer to provide anti-torque reaction. One R&D area requiring effort includes the design and deflection characteristics of the variable position "venetian blinds" which could also be used for thrust modulation and reversal. Another area is the integration of the variable geometry exhaust into the engine performance, including an evaluation of the transient behavior of this system during takeoff and transition.

TABLE 99. PROPULSION SYSTEM TECHNOLOGY NEEDS

Critical Technology	Applicability to Rotorcraft Type	Research Areas	Qualitative Ranking of Importance to Rotorcraft Development	Military Applicability
VIGV Fan	X-Wing or ABC	• Fan Performance Improvement in closed VIGV mode • Operability in closed VIGV mode - Stall - Blade Stresses • Noise Reduction/Suppression • Separator Functions	1	Yes
Integrated Engine/Rotorcraft Control (VIGV Fan or Prop/Shaft)	X-Wing or ABC	• Systems Study of Engine Control using Engine and Rotorcraft Dynamic Models • Propulsion System Integration	2	Yes
Bleed Compressor	X-Wing	• System Integration Studies of Bleed Compressors • VG Compressor Design (Requirements Dependent upon Results of Above Study)	3	Yes
Use of Exhaust for Torque Reaction	X-Wing	• Vectoring Device • Engine Operation/Integration	4	Yes

TABLE 99. PROPULSION SYSTEM TECHNOLOGY NEEDS - Continued

Critical Technology	Applicability to Rotorcraft Type	Research Areas	Qualitative Ranking of Importance to Rotorcraft Development	Military Applicability
Shafts and Bearings (VIGV or Prop/Shaft)	ABC or X-Wing	• Life and Reliability • Elastomeric Shaft Mounting	5	Yes
Internal Engine Clutch	X-Wing or ABC	• Clutch Plate Materials/ Configuration for Increased Energy Absorption Ratio	6	Yes
Traction Drive (Main Rotor Drive or Prop/Shaft X mission)	ABC or X-Wing	• Gear Life and Availability • Weight and Material	7	Yes

SHAFTS AND BEARINGS

Because of the large number of shaft and bearing components involved in these drive systems, the potential exists for improvements in aircraft economics and reliability through the use of advanced materials and manufacturing techniques, and for vibration reduction and improved passenger comfort through the use of elastomeric bearings.

INTERNAL ENGINE CLUTCH

An internal clutch which disengages the fan at takeoff is an alternative to closing VIGV completely. Although the evaluation in this study showed insufficient fuel saved benefit to justify it for a commercial rotorcraft it may still be an attractive feature if fully closed VIGV operation becomes a problem because of noise, stress or stall margin limitations revealed by test. Two R&D areas are envisioned for clutch development. Test programs to evaluate the power absorption characteristics of a variety of materials and surface types. Full scale fan engine tests for the development of a clutch design which can withstand the vibratory loads transmitted from the fan.

TRACTION DRIVES

No traction drive application was identified in the convertible engines on their transmissions up to the main rotor. It is believed, however, that the main rotor itself offers a large potential weight savings with a traction drive. Since the data base consists of research projects at very small power levels, it is recommended that R&D in large power scale be considered with the main rotor application.

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APPENDIX A - ABC FINAL ENGINE PERFORMANCE DATA IN MISSION SIZE

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SEA LEVEL, STATIC
CONSTANT OUTPUT SHAFT SPEED

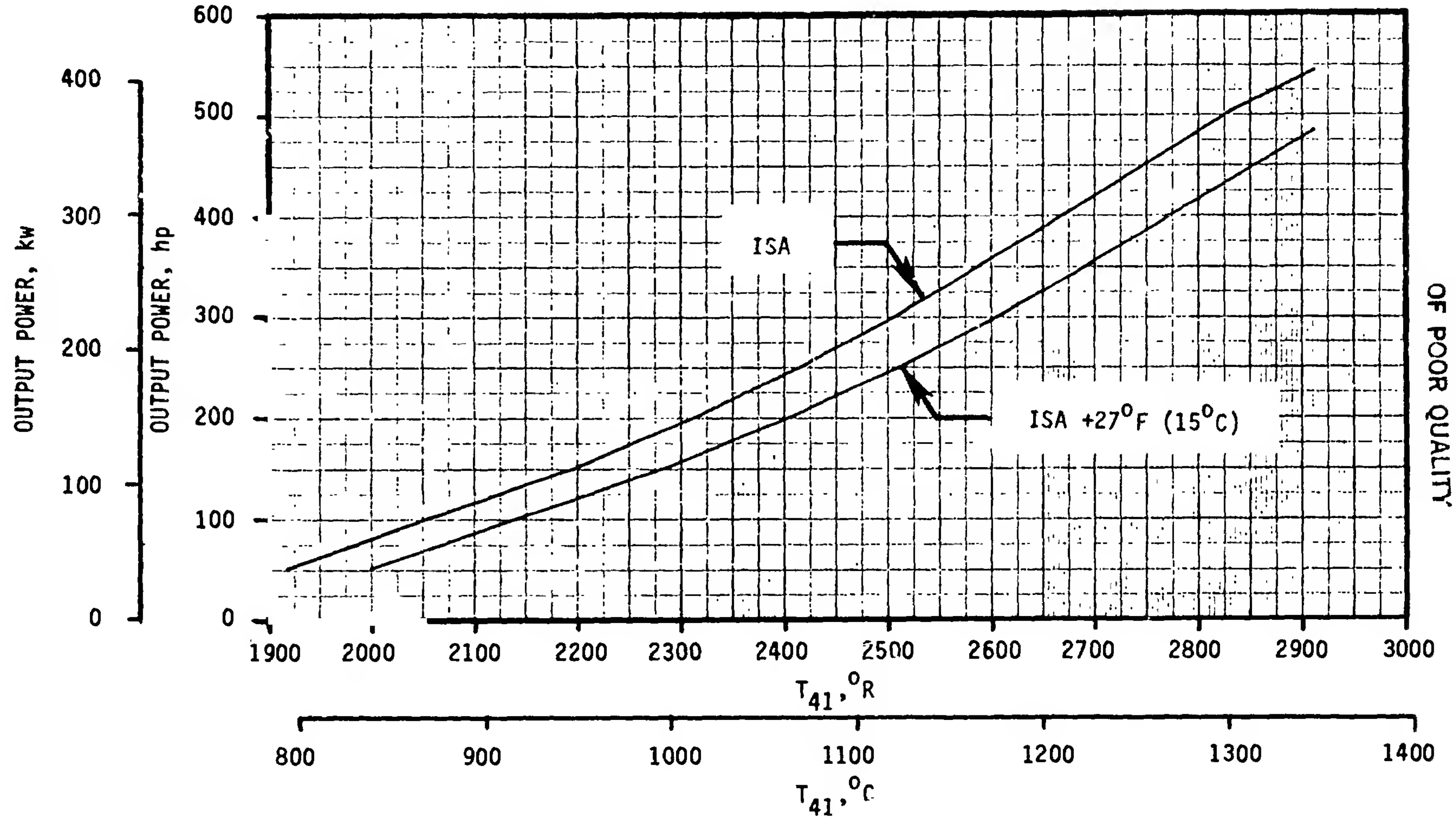

Figure A1. Power vs T_{41} at Hover

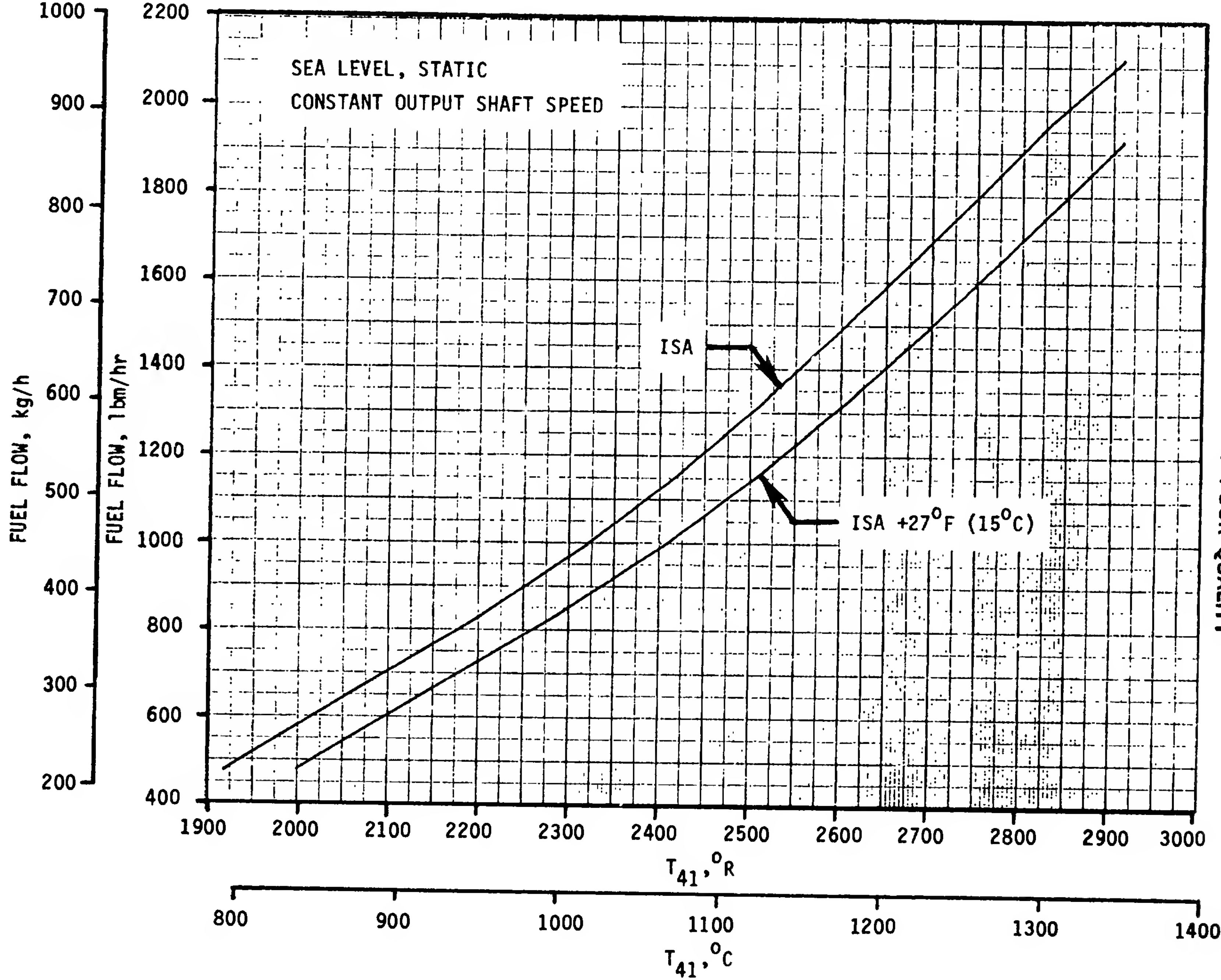

Figure A2. Fuel Flow vs T_{41} at Hover

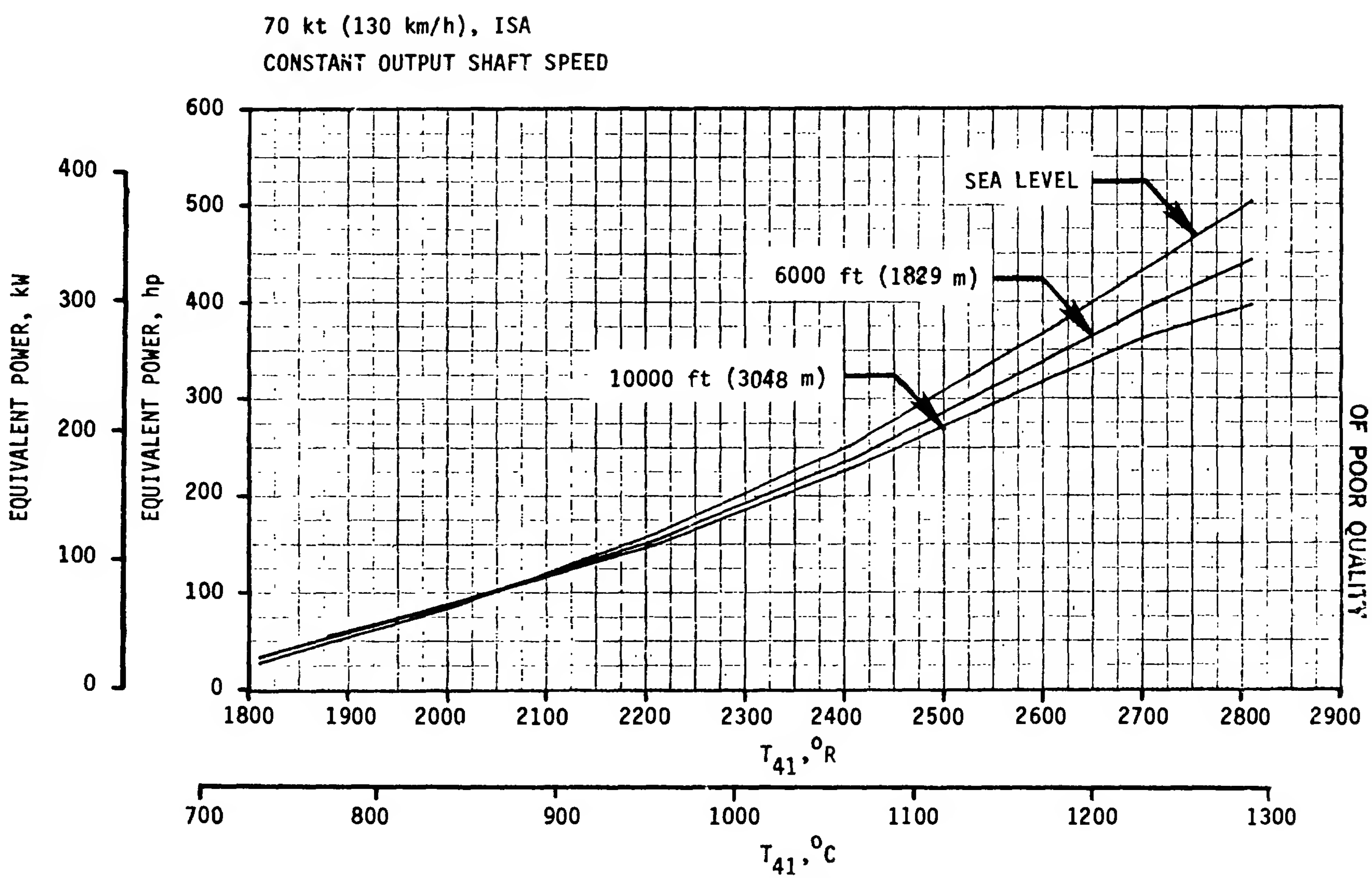

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Figure A3. Equivalent Power vs T_{41} at Typical Climb Flight Conditions

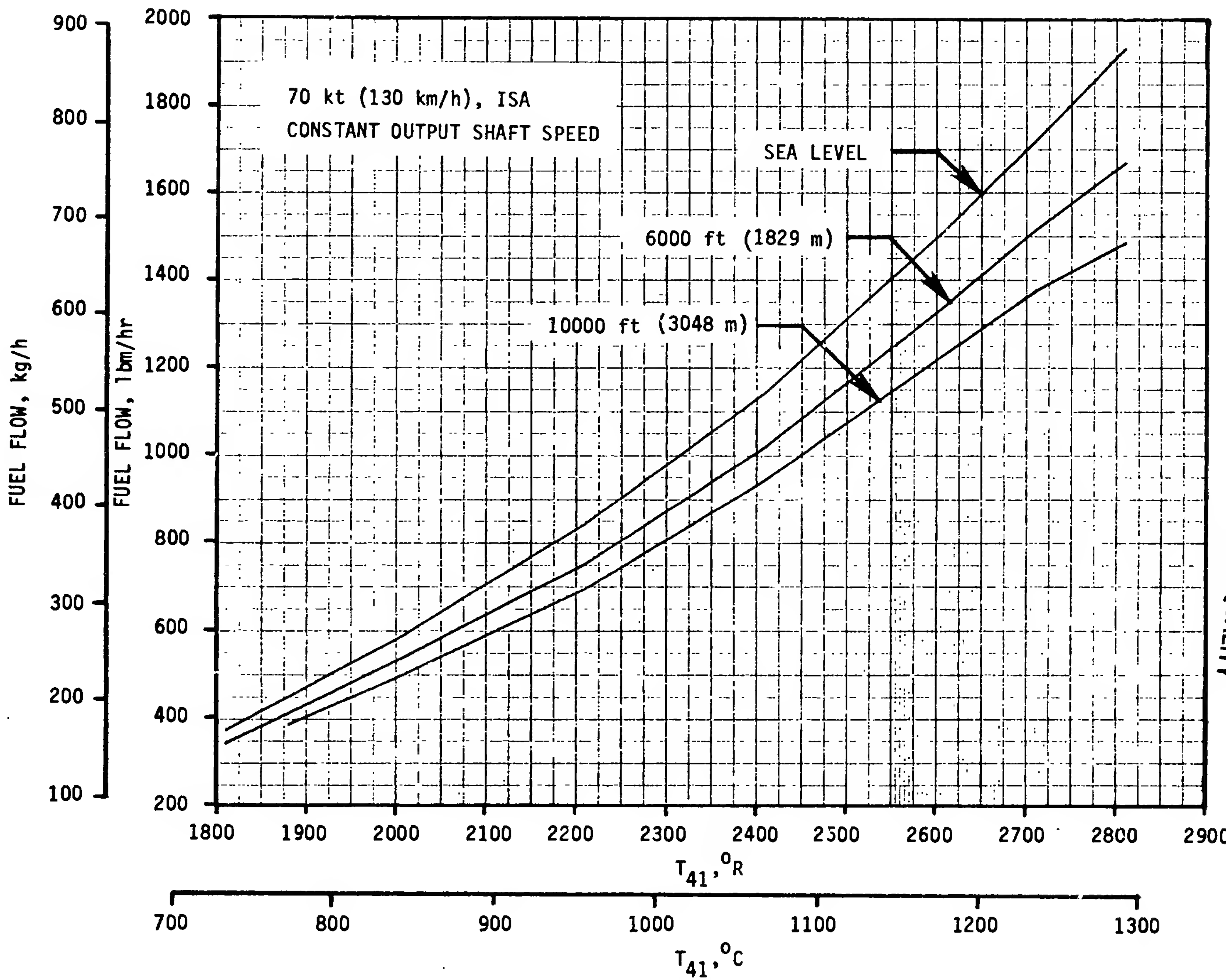

Figure A4. Fuel Flow vs T_{41} at Typical Climb Flight Conditions

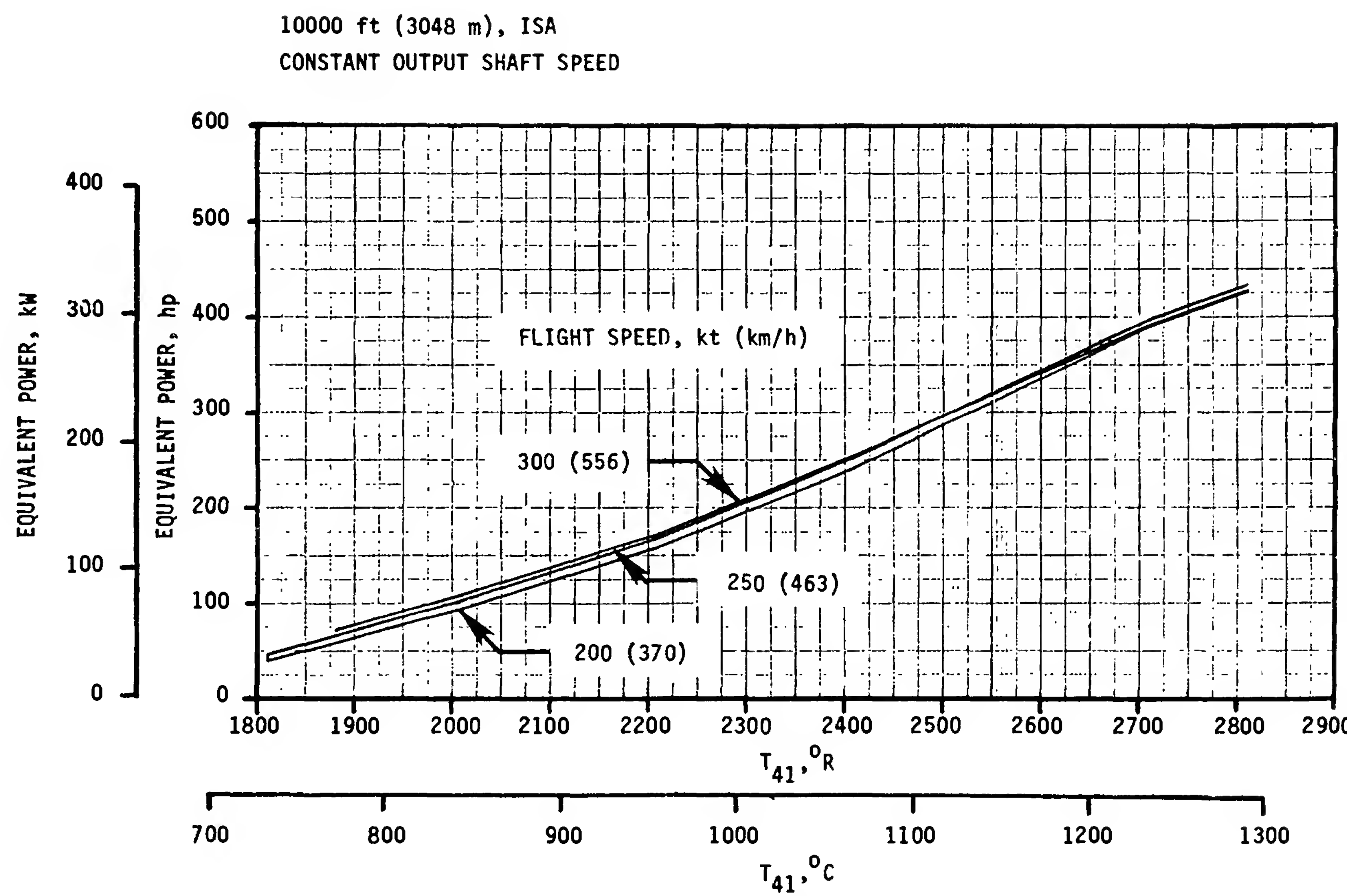

Figure A5. Equivalent Power vs T_{41} and Flight Speed at Cruise

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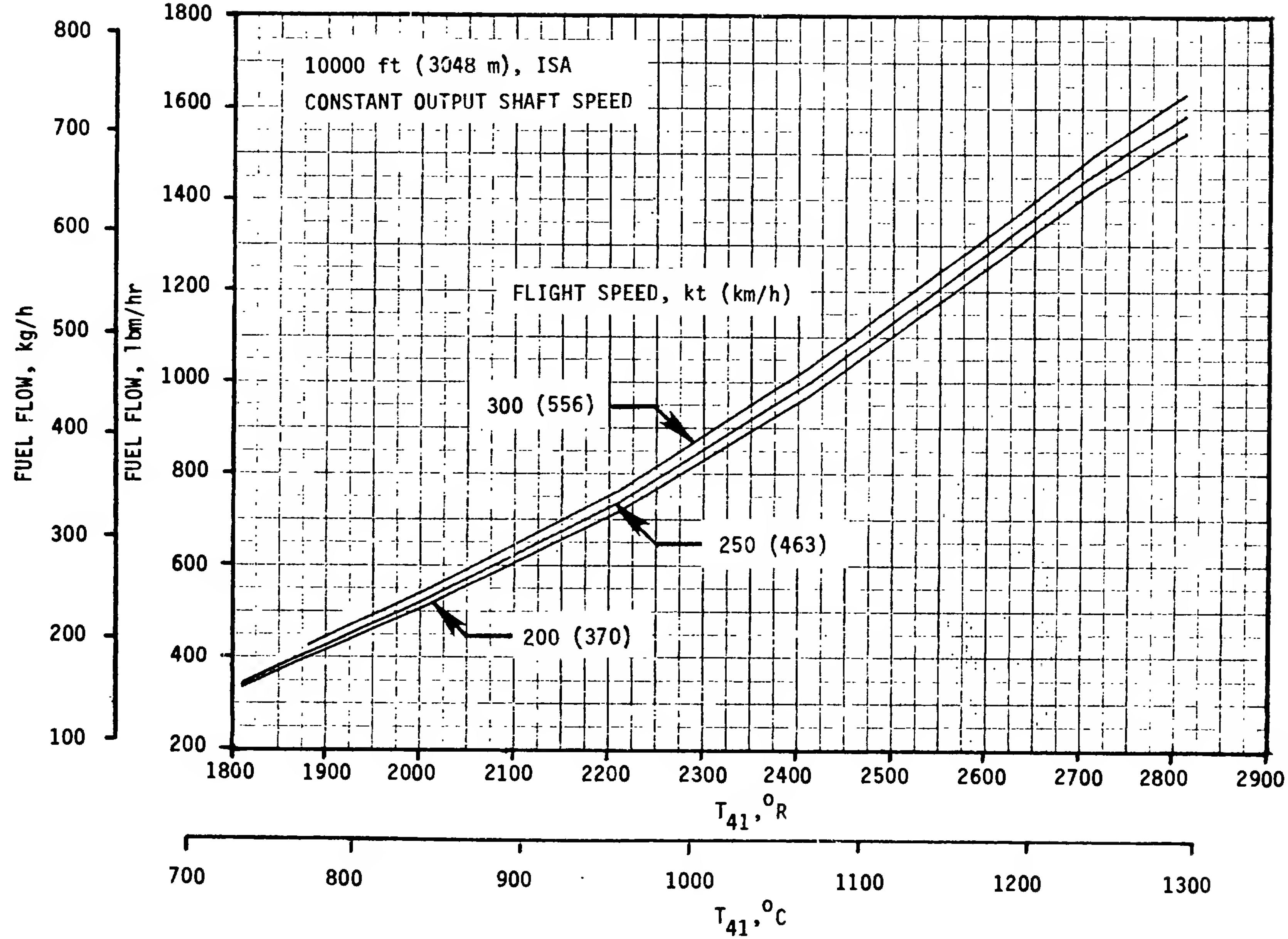

Figure A6. Fuel Flow vs T_{41} and Flight Speed at Cruise

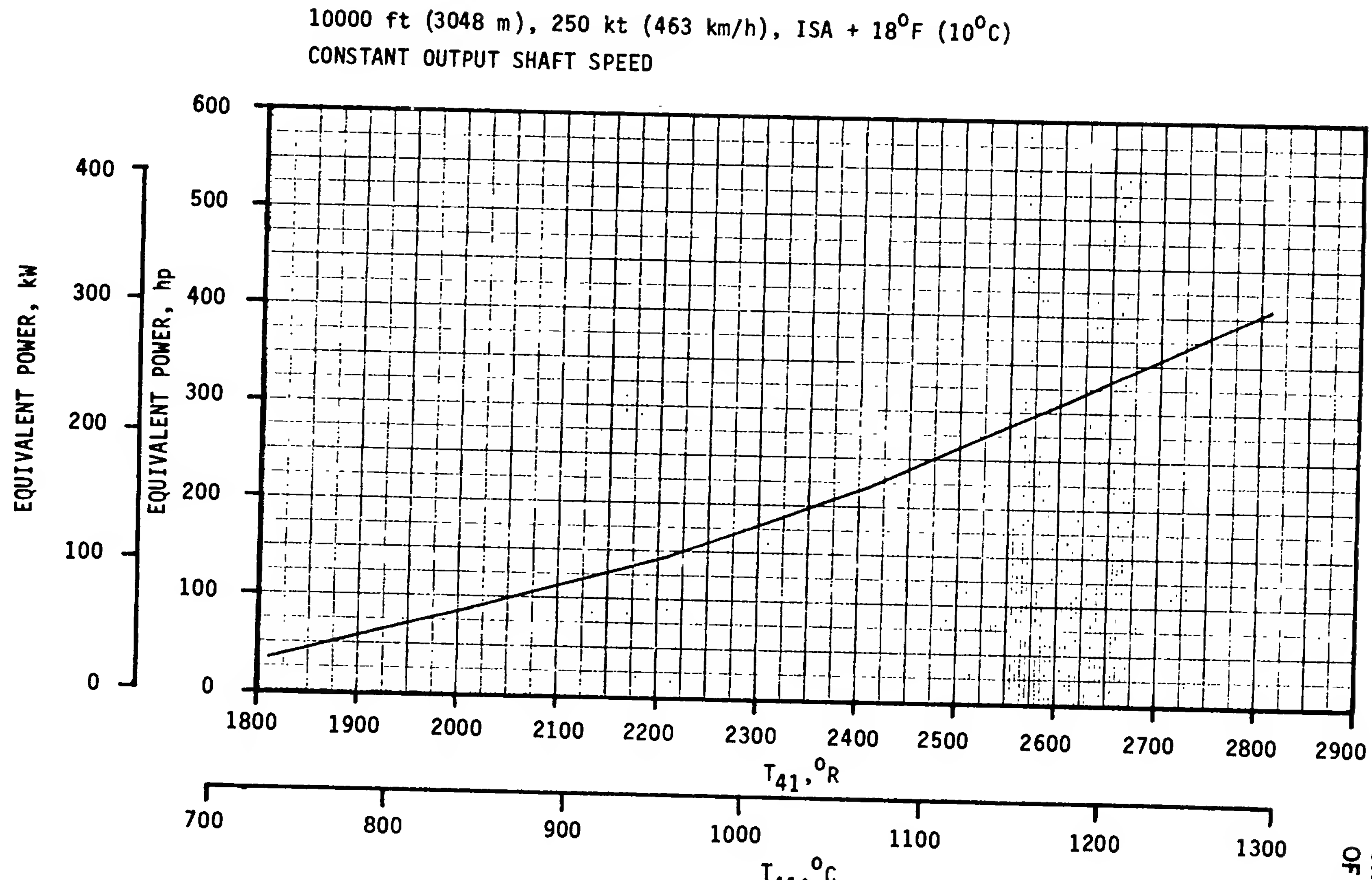

Figure A7. Equivalent Power vs T_{41} at Design Cruise

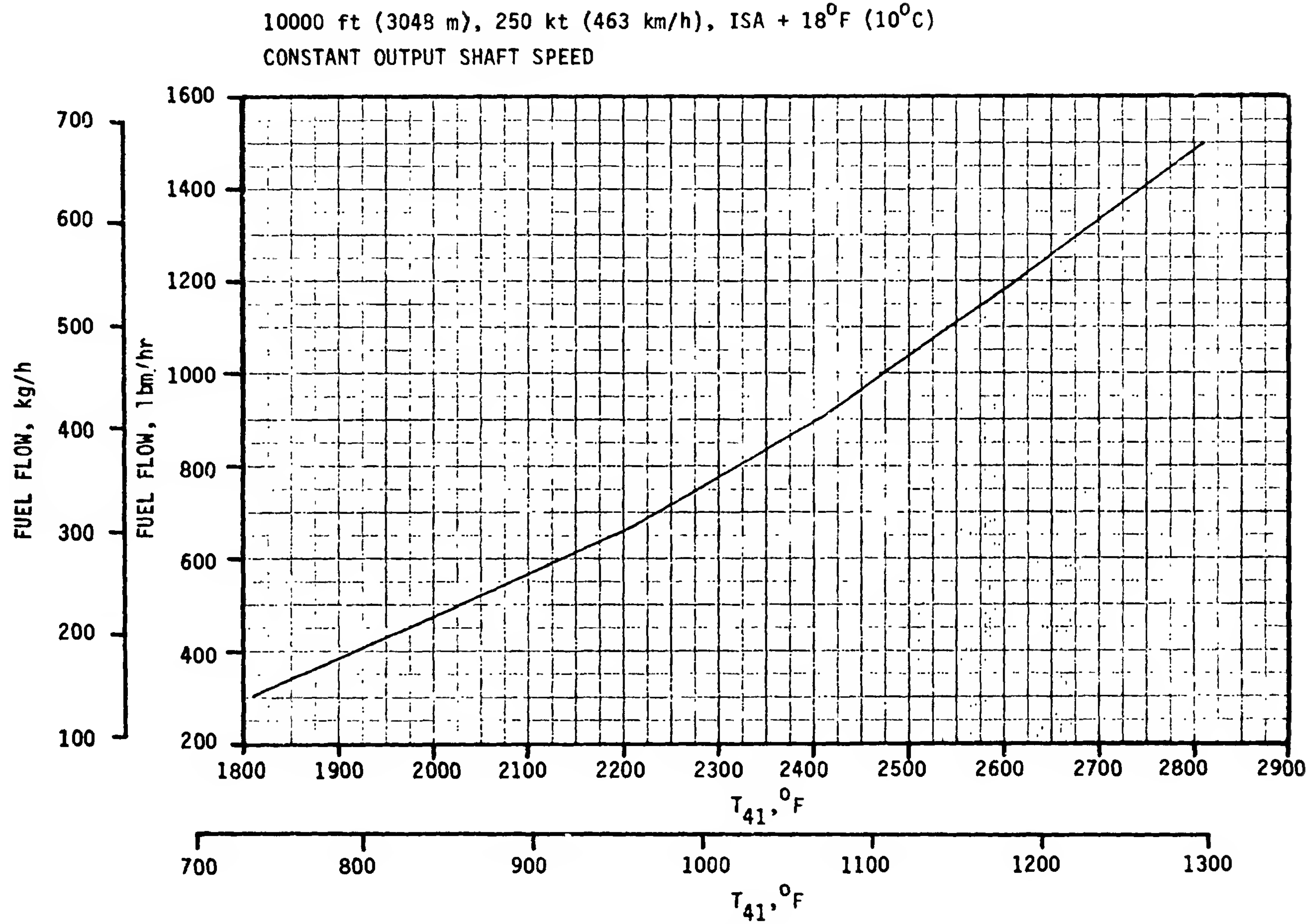

Figure A8. Fuel Flow vs T_{41} at Design Cruise

APPENDIX B - X-WING FINAL ENGINE PERFORMANCE DATA IN MISSION SIZE

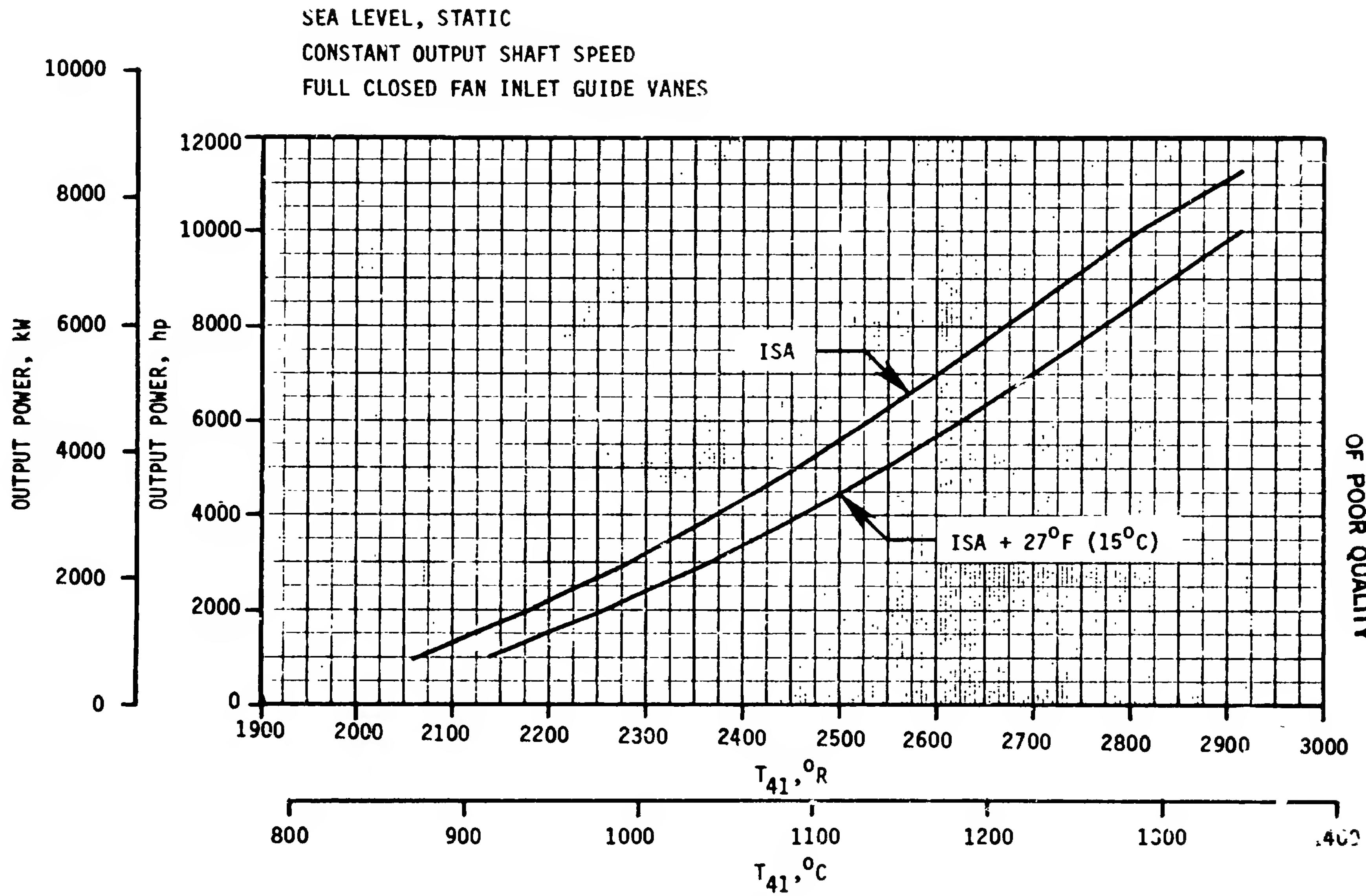

Figure B1. Power vs T_{41} at Hover

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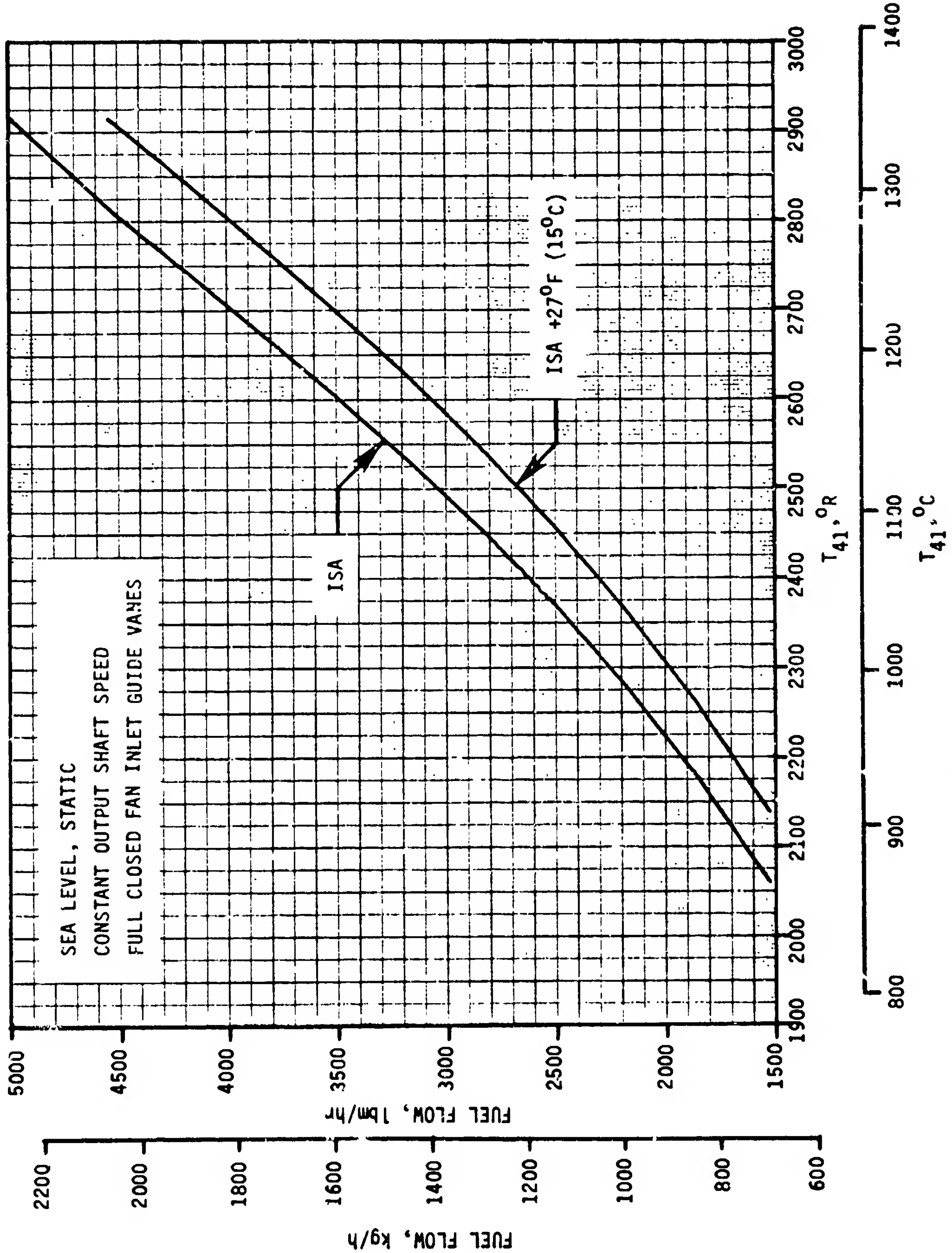

Figure B2. Fuel Flow vs T_{41} at Hover

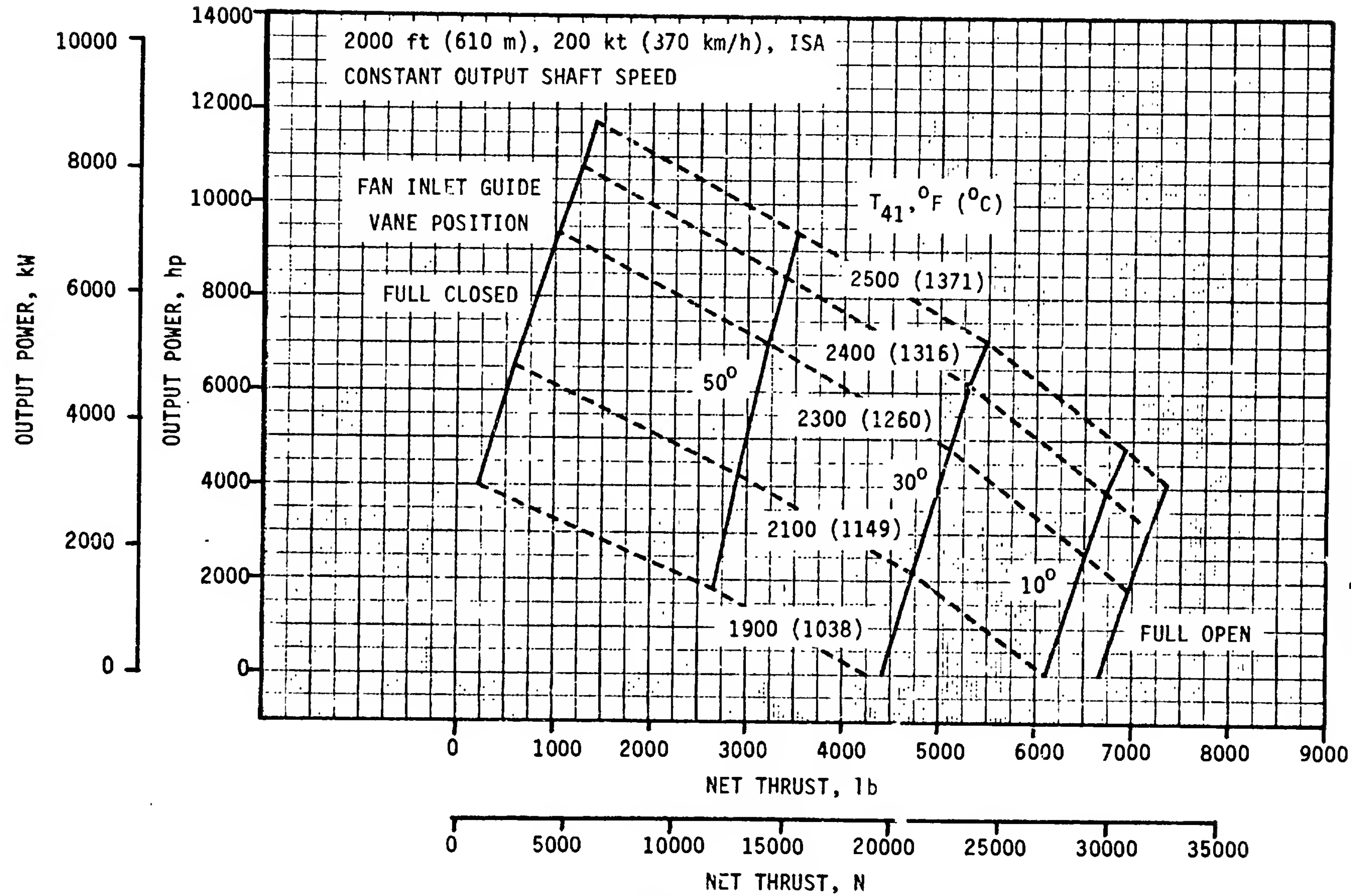

Figure B3. Power vs Thrust at Typical Conversion Flight Condition

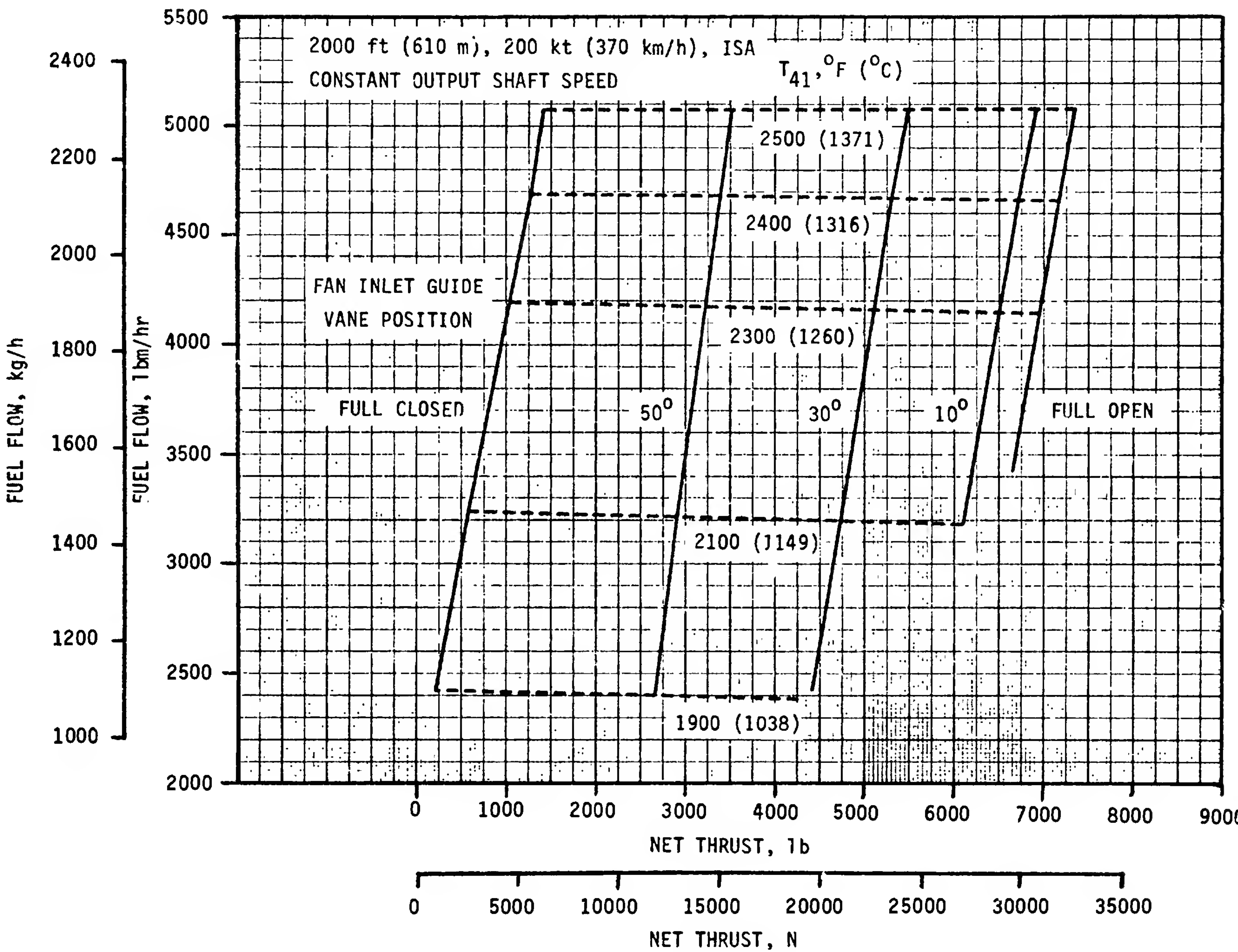

Figure B4. Fuel Flow vs Thrust at Typical Conversion Flight Condition

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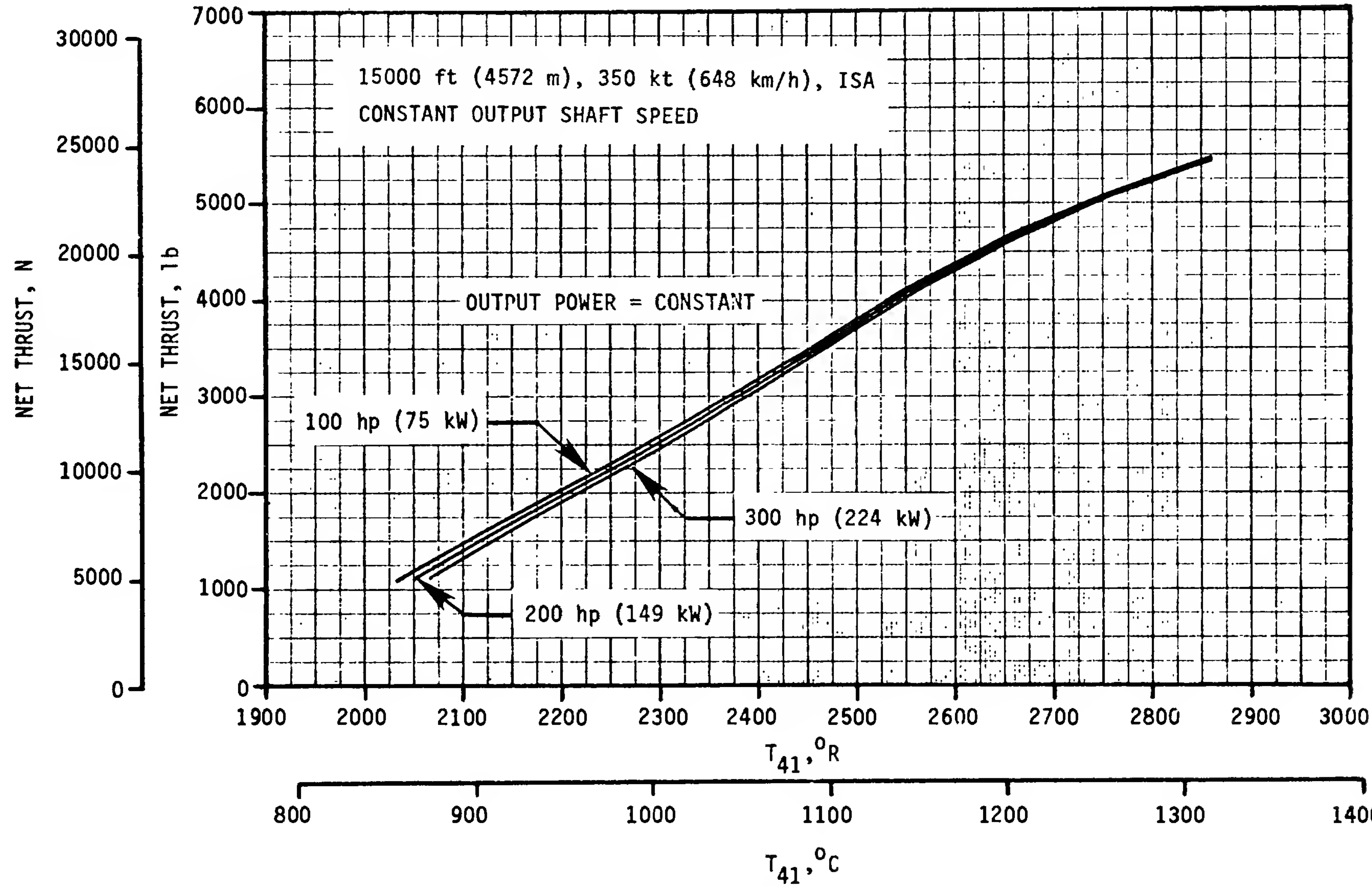

Figure B5. Thrust vs T_{41} at Typical Climb Flight Condition

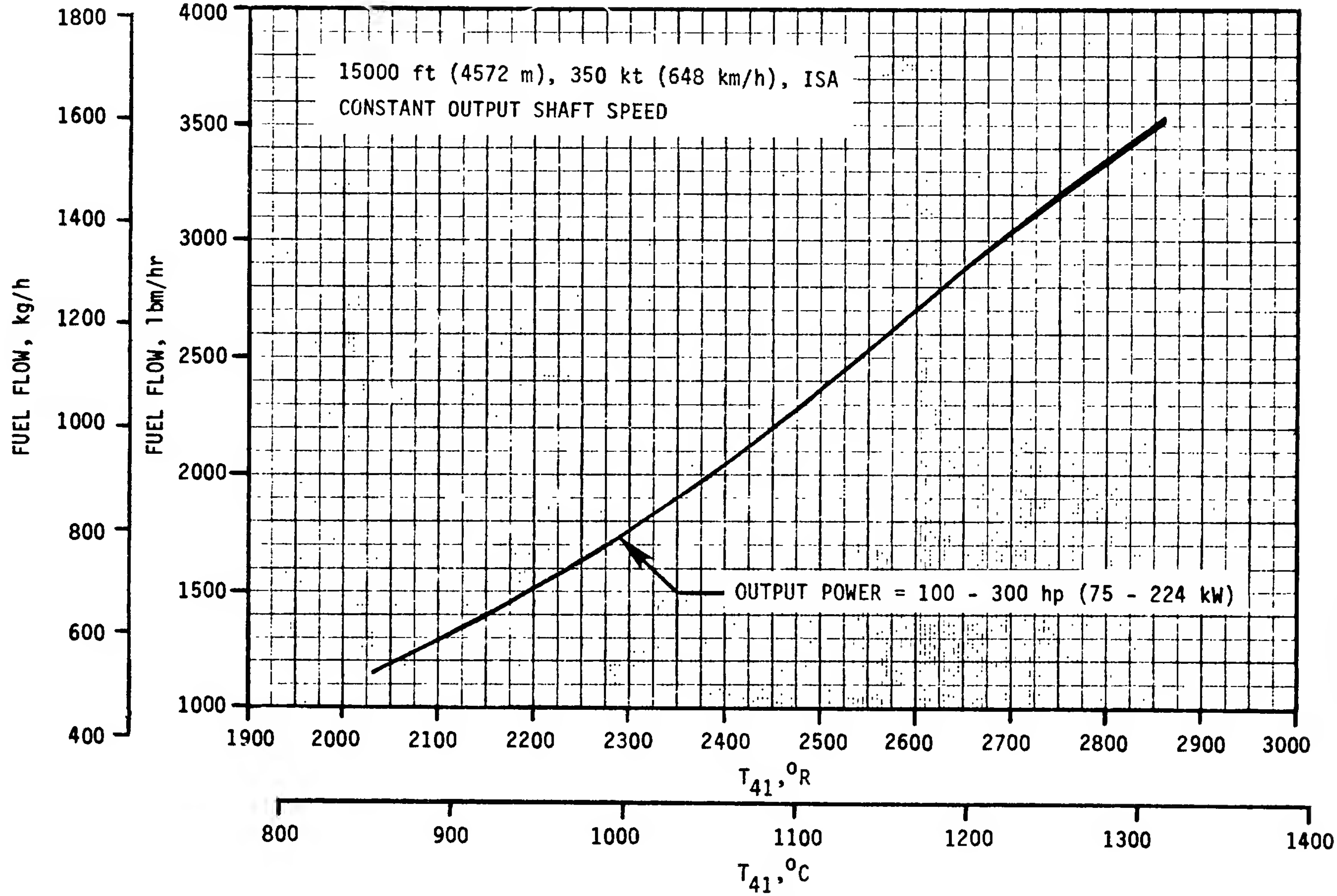

Figure B6. Fuel Flow vs T_{41} at Typical Climb Flight Condition

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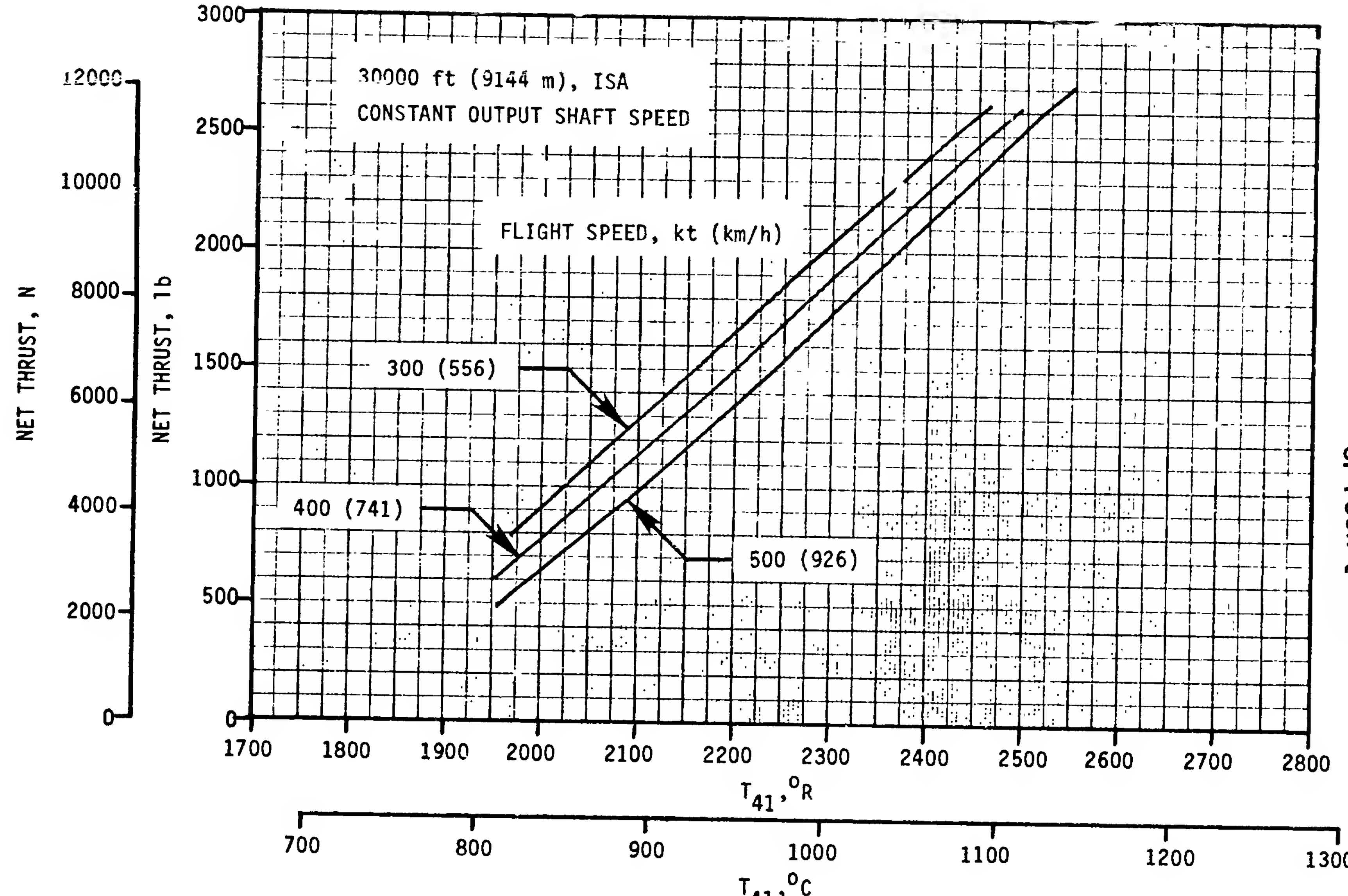

Figure B7. Thrust vs T_{41} and Flight Speed at Cruise

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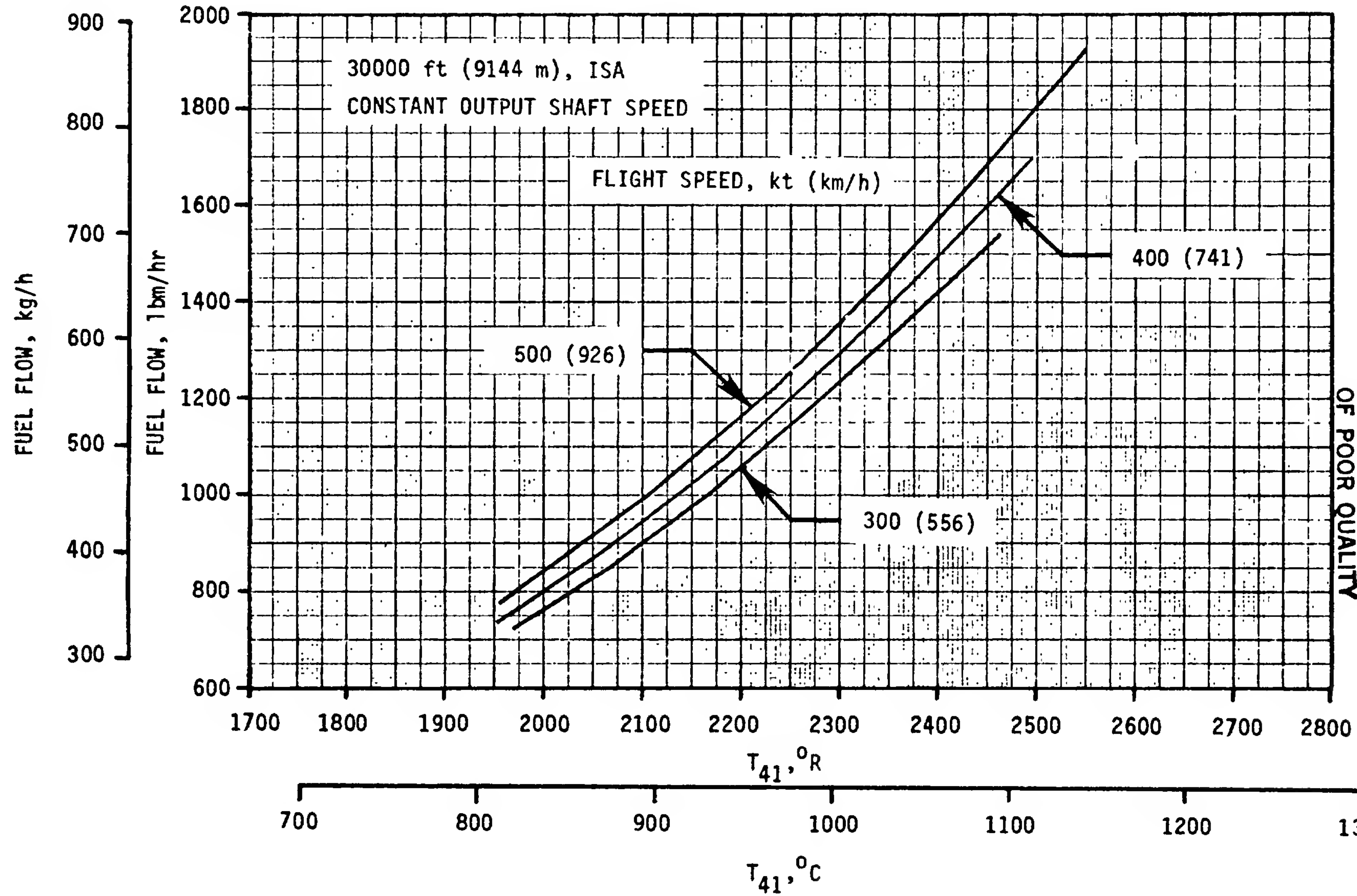

Figure B8. Fuel Flow vs T_{41} and Flight Speed at Cruise

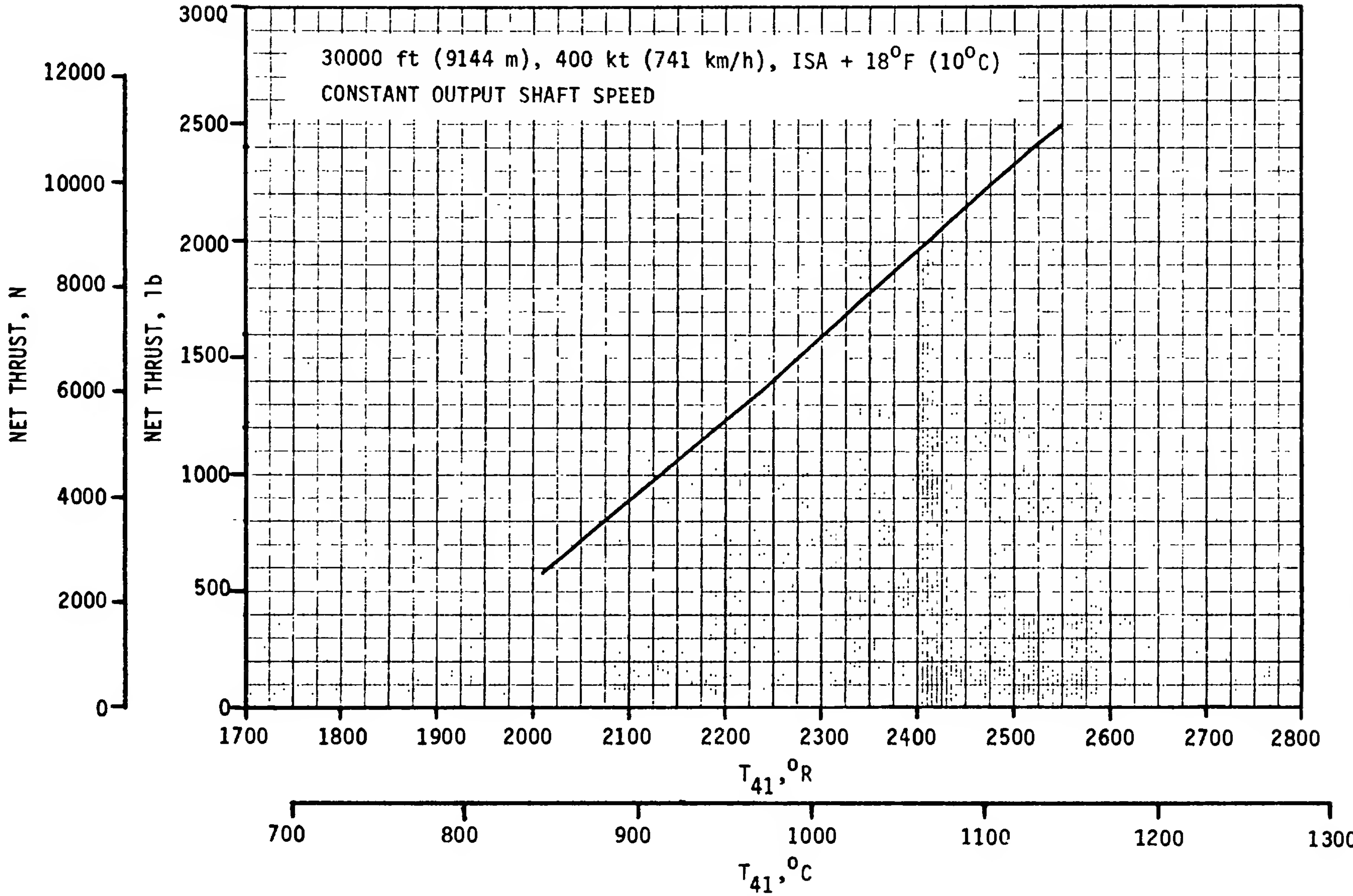

Figure B9. Thrust vs T_{41} at Design Cruise

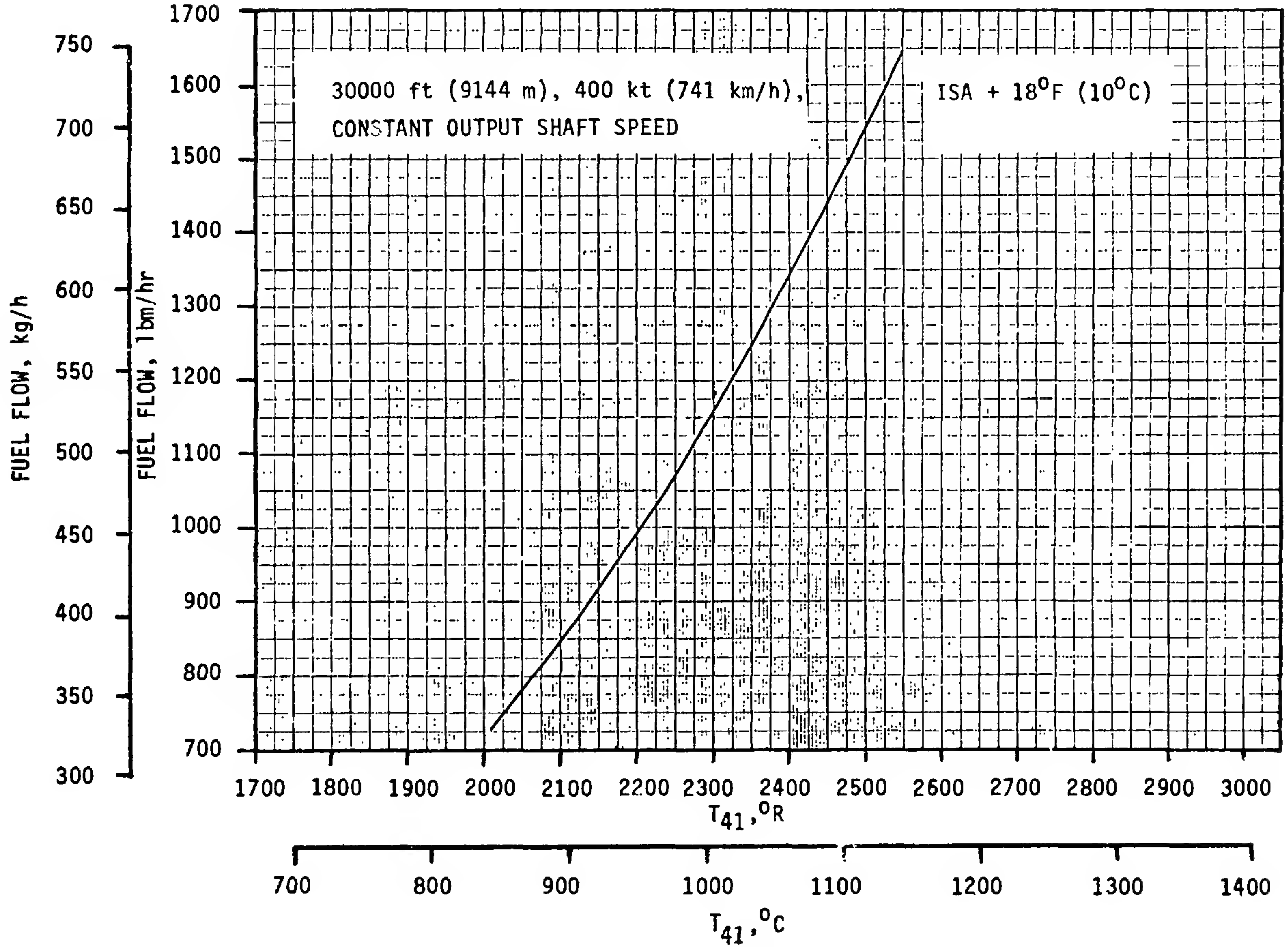

Figure B10. Fuel Flow vs T_{41} at Design Cruise

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